

Welding Inspection

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Typical Duties of Welding Inspectors

1 General

Welding Inspectors are employed to assist with the quality control (QC) activities that are necessary to ensure that welded items will meet specified requirements and be fit for their application.

For employers to have confidence in their work, Welding Inspectors need to have the ability to understand/interpret the various QC procedures and also have sound knowledge of welding technology.

Visual inspection is one of the non-destructive examination (NDE) disciplines and for some applications may be the only form.

For more demanding service conditions, visual inspection is usually followed by one or more of the other non-destructive testing (NDT) techniques – surface crack detection and volumetric inspection of butt welds.

Application Standards/Codes usually specify (or refer to other standards) that give the acceptance criteria for weld inspection and may be very specific about the particular techniques to be used for surface crack detection and volumetric inspection, they do not usually give any guidance about basic requirements for visual inspection.

Guidance and basic requirements for visual inspection are given by:

BS EN 970 (Non-destructive Examination of Fusion Welds – Visual Examination)

1.1 Basic Requirements for Visual Inspection (to BS EN 970)

BS EN 970 provides the following:

- Requirements for welding inspection personnel.
- Recommendations about conditions suitable for visual examination.
- The use of gauges/inspection aids that may be needed/helpful for inspection.
- Guidance about information that may need to be included in the inspection records.
- Guidance about when inspection may be required during the stages of fabrication.

A summary of each of these topics is given in the following sections.

1.2 Welding Inspection Personnel

Before starting work on a particular contract, BS 970 states that Welding Inspectors should:

- Be familiar with relevant standards*, rules and specifications for the fabrication work that is to be undertaken
- Be informed about the welding procedure(s) to be used
- Have good vision – in accordance with EN 473 and should be checked every 12 months

(standards may be National or Client)*

BS EN 970 does not give or make any recommendation about a formal qualification for visual inspection of welds. However, it has become industry practice for inspectors to have practical experience of welding inspection together with a recognised qualification in Welding Inspection – such as a CSWIP Qualification.

1.3 Conditions for Visual Inspection

Illumination

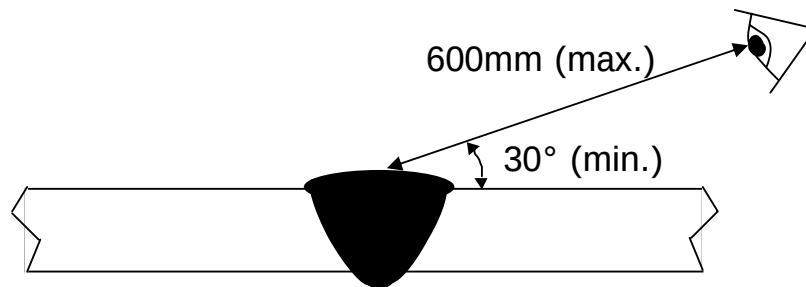
BS EN 970 states that the minimum illumination **shall** be 350 lux but recommends a minimum of 500 lux*.

** normal shop or office lighting*

Access

Access to the surface, for direct inspection, should enable the eye to be:

- Within 600mm of the surface being inspected
- In a position to give a viewing angle of not less than 30°



1.4 Aids to Visual Inspection

Where access is restricted for direct visual inspection, the use of a mirrored boroscope, or a fibre optic viewing system, are options that may be used – usually by agreement between the contracting parties.

It may also be necessary to provide auxiliary lighting to give suitable contrast and relief effect between surface imperfections and the background.

Other items of equipment that may be appropriate, to facilitate visual examination, are:

- Welding gauges (for checking bevel angles and weld profile, fillet sizing, measuring undercut depth).
- Dedicated weld gap gauges and linear misalignment (high–low) gauges.
- Straight edges and measuring tapes.
- Magnifying lens (if a magnification lens is used to aid visual examination it should be X2 to X5).

BS 970 has schematics of a range of welding gauges together with details of what they can be used for and the precision of the measurements that can be made.

1.5 Stages When Inspection May Be Required

BS EN 970 states that examination is normally performed on welds in the **as-welded condition**. This means that visual inspection of the finished weld is a minimum requirement.

However, BS EN 970 goes on to say that the extent of examination, and the stages when some inspection activity is required, should be specified by the Application Standard or by agreement between client and fabricator.

For fabricated items that must have high integrity, such as pressure vessels and piping or large structures inspection activity will usually be required throughout the fabrication process, namely:

- Before welding
- During welding
- After welding

Inspection activities at each of these stages of fabrication can be considered to be the **Duties of the Welding Inspector** and typical inspection checks that may be required are described in the following section.

1.6 Typical Duties of a Welding Inspector

The relevant standards, rules and specifications that a Welding Inspector should be familiar with at the start of a new contract are all the documents he will need to refer to during the fabrication sequence in order to make judgements about particular details.

Typical **documents** that may need to be referred to are:

- The Application Standard (or Code)
(for visual acceptance criteria – see note below)*
- Quality plans or inspection check lists
(for the type and extent of inspection)
- Drawings
(for assembly/fit-up details and dimensional requirements)
- QC procedures
(Company QC/QA procedures such as those for document control, material handling, electrode storage and issue, WPSs etc)

Note: Although most of the requirements for the fabricated item should be specified by National Standards, Client Standards or various QC Procedures, some features are not easy to define precisely and the requirement may be given as **to good workmanship standard.*

Examples of requirements that are difficult to define precisely are some shape tolerances, distortion, surface damage or the amount of weld spatter.

Good workmanship is the standard that a competent worker should be able to achieve without difficulty when using the correct tools in a particular working environment.

In practice the application of the fabricated item will be the main factor that influences what is judged to be good workmanship or the relevant client specification will determine what is the acceptable level of workmanship.

Reference samples are sometimes needed to give guidance about the acceptance standard for details such as weld surface finish and toe blend, weld root profile and finish required for welds that need to be dressed – by grinding or finishing.

A Welding Inspector should also ensure that any inspection aids that will be needed are:

- In good condition
- Calibrated – as appropriate/as specified by QC procedures

Safety 'consciousness' is a duty of all employees and a Welding Inspector should:

- Be aware of all safety regulations for the workplace
- Ensure that safety equipment that will be needed is available and in suitable condition

Duties before welding

Check	Action
Material	In accordance with drawing/WPS Identified and can be traced to a test certificate In suitable condition (free from damage and contamination)
WPSs	Have been approved and are available to welders (and inspectors)
Welding equipment	In suitable condition and calibrated as appropriate
Weld preparations	In accordance with WPS (and/or drawings)
Welder qualifications	Identification of welders qualified for each WPS to be used. All welder qualification certificates are valid (in date)
Welding consumables	Those to be used are as specified by the WPSs are being stored/controlled as specified by the QC procedure
Joint fit-ups	In accordance with WPS/drawings tack welds are to good workmanship standard and to code/WPS
Weld faces	Are free from defects, contamination and damage
Preheat (if required)	Minimum temperature is in accordance with WPS

Duties during welding

Check	Action
Site/field welding	Ensure weather conditions are suitable/comply with Code (<i>conditions will not affect welding</i>)
Welding process	In accordance with WPS
Preheat (if required)	Minimum temperature is being maintained in accordance with WPS
Interpass temperature	Maximum temperature is in accordance with WPS
Welding consumables	In accordance with WPS and being controlled as procedure
Welding parameters	Current, volts, travel speed are in accordance with WPS
Root run	Visually acceptable to Code (before filling the joint) (<i>for single sided welds</i>)
Gouging/grinding	By an approved method and to good workmanship standard
Interrun cleaning	To good workmanship standard
Welder	On the approval register/qualified for the WPS being used

Duties after welding

Check

Weld identification

Weld appearance

Dimensional survey

Drawings

NDT

Repairs

PWHT (if required)

Pressure/load test
(if required)

Documentation
records

Action

Each weld is marked with the welder's identification and is identified in accordance with drawing/weld map

Ensure welds are suitable for **all** NDT (profile, cleanliness etc)
Visually inspect welds and sentence in accordance with Code

Check dimensions are in accordance with drawing/Code

Ensure any modifications are included on as-built drawings

Ensure all NDT is complete and reports are available for records

Monitor in accordance with the procedure

Monitor for compliance with procedure (check chart record)

Ensure test equipment is calibrated
Monitor test to ensure compliance with procedure/Code.

Ensure reports/records are available

Ensure all reports/records are completed and collated as required

1.7 Examination Records

The requirement for examination records/inspection reports will vary according to contract and type of fabrication and there is frequently no requirement for a formal record.

When an inspection record is required it may be necessary to show that items have been checked at the specified stages and that they have satisfied the acceptance criteria.

The form of this record will vary – possibly a signature against an activity on an Inspection Checklist or on a Quality Plan, or it may be an individual inspection report for each item.

For individual inspection reports, BS EN 970 lists typical details for inclusion such as:

- Name of manufacturer/fabricator
- Identification of item examined
- Material type and thickness
- Type of joint
- Welding process
- Acceptance standard/criteria
- Locations and types of all imperfections not acceptable
(When specified, it may be necessary to include an accurate sketch or photograph.)
- Name of examiner/inspector and date of examination

1 Terms and Definitions

Note:

The following definitions are taken from BS 499-1:1991 'Welding terms and symbols – Glossary for welding, brazing and thermal cutting'.

Brazing

A process of joining generally applied to metals in which, during or after heating, molten filler metal is drawn into or retained in the space between closely adjacent surfaces of the parts to be joined by capillary attraction. In general, the melting point of the filler metal is above 450°C but always below the melting temperature of the parent material.

Braze welding

The joining of metals using a technique similar to fusion welding and a filler metal with a lower melting point than the parent metal, but neither using capillary action as in brazing nor intentionally melting the parent metal.

Joint

A connection where the individual components, suitably prepared and assembled, are joined by welding or brazing.

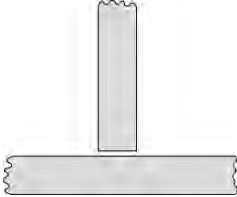
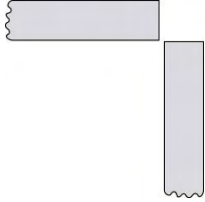
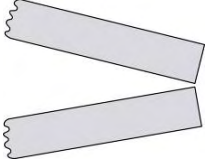
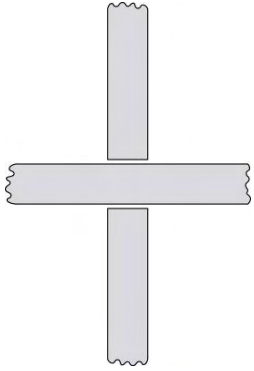
Weld

A union of pieces of metal made by welding.

Welding

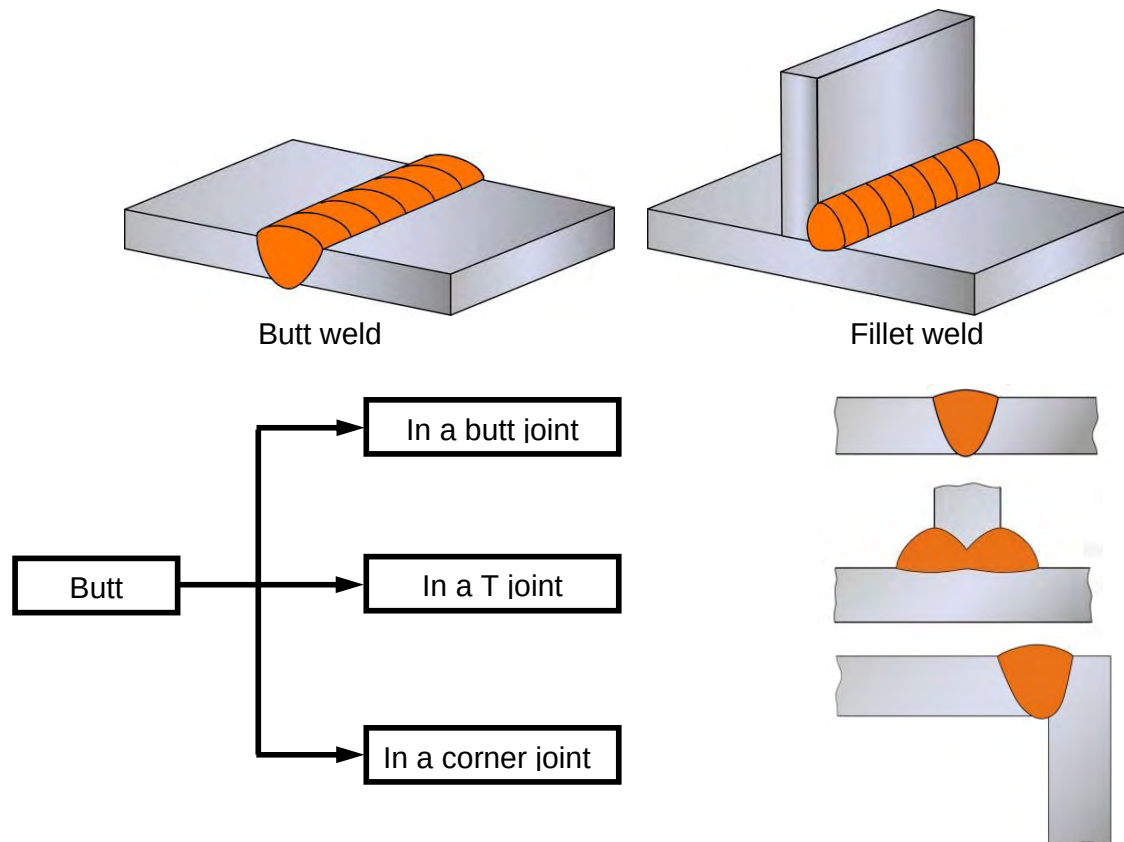
An operation in which two or more parts are united by means of heat or pressure or both, in such a way that there is continuity in the nature of the metal between these parts.

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Type of joint	Sketch	Definition
Butt joint		A connection between the ends or edges of two parts making an angle to one another of 135 to 180° inclusive in the region of the joint.
T joint		A connection between the end or edge of one part and the face of the other part, the parts making an angle to one another of more than 5 up to and including 90° in the region of the joint
Corner joint		A connection between the ends or edges of two parts making an angle to one another of more than 30 but less than 135° in the region of the joint
Edge joint		A connection between the edges of two parts making an angle to one another of 0 to 30° inclusive in the region of the joint
Cruciform joint		A connection in which two flat plates or two bars are welded to another flat plate at right angles and on the same axis
Lap joint		A connection between two overlapping parts making an angle to one another of 0 to 5° inclusive in the region of the weld or welds

2 Types of Weld

2.1 From the configuration point of view (as per 2.2)

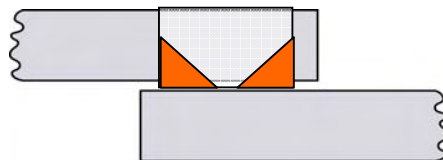


Autogenous weld

A fusion weld made without filler metal which can be achieved by TIG, plasma, electron beam, laser or oxy-fuel gas welding.

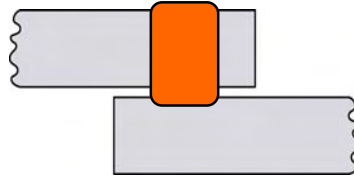
Slot weld

A joint between two overlapping components made by depositing a fillet weld round the periphery of a hole in one component so as to join it to the surface of the other component exposed through the hole.



Plug weld

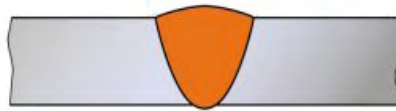
A weld made by filling a hole in one component of a workpiece with filler metal so as to join it to the surface of an overlapping component exposed through the hole (the hole can be circular or oval).



2.2 From the penetration point of view

Full penetration weld

A welded joint where the weld metal fully penetrates the joint with complete root fusion. In US the preferred term is complete joint penetration weld (CJP) (see AWS D1.1.).



Partial penetration weld:

A welded joint without full penetration. In US the preferred term is partial joint penetration weld (PJP).

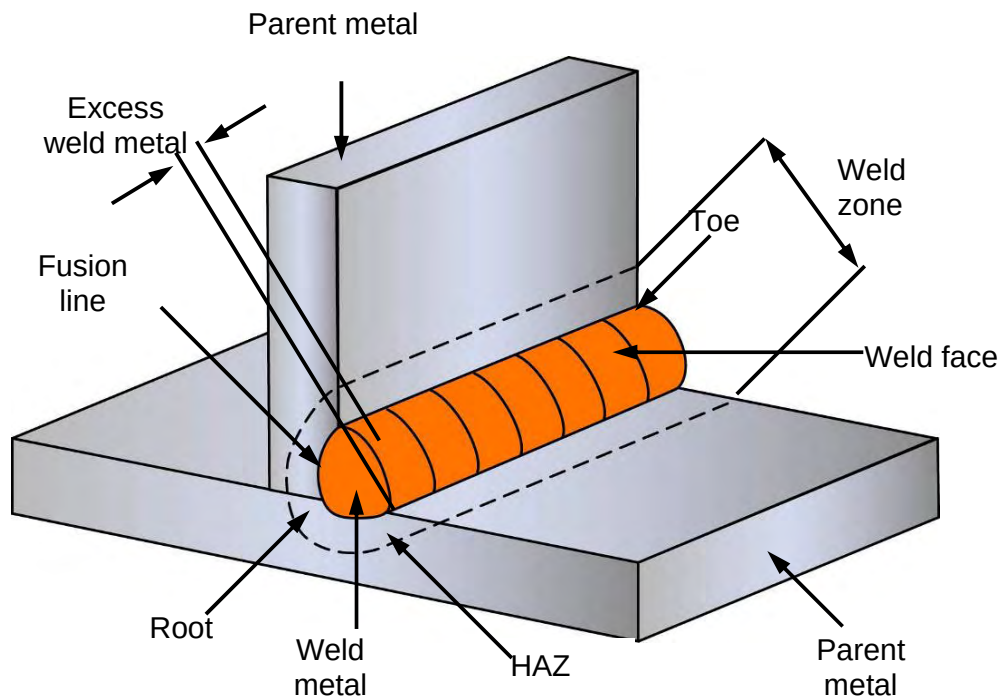
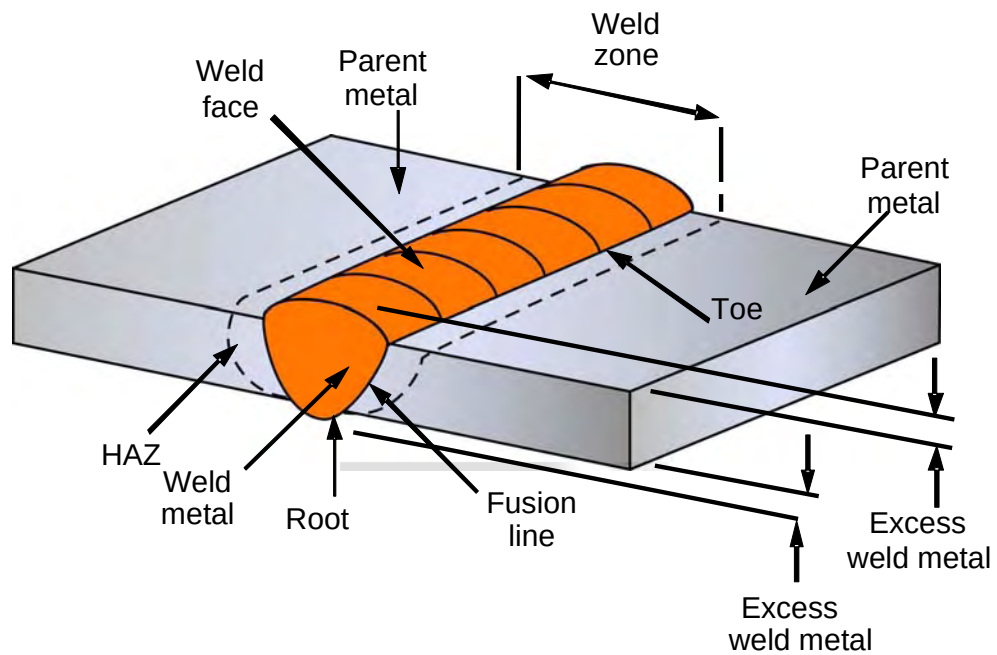


3 Types of Joints (see BS EN ISO 15607)

- **Homogeneous:** Welded joint in which the weld metal and parent material have no significant differences in mechanical properties and/or chemical composition. Example: Two carbon steel plates welded with a matching carbon steel electrode.
- **Heterogeneous:** Welded joint in which the weld metal and parent material have significant differences in mechanical properties and/or chemical composition. Example: A repair weld of a cast iron item performed with a nickel-based electrode.
- **Dissimilar:** Welded joint in which the parent materials have significant differences in mechanical properties and/or chemical composition. Example: A carbon steel lifting lug welded onto an austenitic stainless steel pressure vessel.

4 Features of the Completed Weld

- **Parent metal:** Metal to be joined or surfaced by welding, braze welding or brazing.
- **Filler metal:** Metal added during welding, braze welding, brazing or surfacing.
- **Weld metal:** All metal melted during the making of a weld and retained in the weld.
- **Heat-affected zone (HAZ):** The part of the parent metal that is metallurgically affected by the heat of welding or thermal cutting, but not melted.
- **Fusion line:** The boundary between the weld metal and the HAZ in a fusion weld. This is a non-standard term for weld junction.
- **Weld zone:** The zone containing the weld metal and the HAZ.
- **Weld face:** The surface of a fusion weld exposed on the side from which the weld has been made.
- **Root:** The zone on the side of the first run furthest from the welder.
- **Toe:** The boundary between a weld face and the parent metal or between runs. This is a very important feature of a weld since toes are points of high stress concentration and often they are initiation points for different types of cracks (eg fatigue cracks, cold cracks). In order to reduce the stress concentration, toes must blend smoothly into the parent metal surface.
- **Excess weld metal:** Weld metal lying outside the plane joining the toes. Other non-standard terms for this feature: Reinforcement, overfill.



5 Weld Preparation

A preparation for making a connection where the individual components, suitably prepared and assembled, are joined by welding or brazing.

5.1 Features of the weld preparation

Angle of bevel

The angle at which the edge of a component is prepared for making a weld.

For an MMA weld on carbon steel plates, the angle is:

- 25-30° for a V preparation.
- 8-12° for a U preparation.
- 40-50° for a single bevel preparation.
- 10-20° for a J preparation.

Included angle

The angle between the planes of the fusion faces of parts to be welded. In the case of single V or U and double V or U this angle is twice the bevel angle. In the case of single or double bevel, single or double J bevel, the included angle is equal to the bevel angle.

Root face

The portion of a fusion face at the root that is not bevelled or grooved. Its value depends on the welding process used, parent material to be welded and application; for a full penetration weld on carbon steel plates, it has a value between 1-2mm (for the common welding processes).

Gap

The minimum distance at any cross section between edges, ends or surfaces to be joined. Its value depends on the welding process used and application; for a full penetration weld on carbon steel plates, it has a value between 1-4mm.

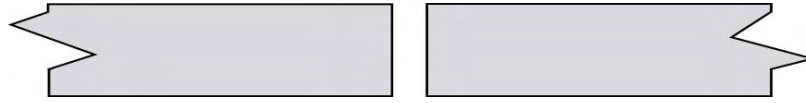
Root radius

The radius of the curved portion of the fusion face in a component prepared for a single J or U, double J or U weld. In case of MMA, MIG/MAG and oxy-fuel gas welding on carbon steel plates, the root radius has a value of 6mm for single and double U preparations and 8mm for single and double J preparations.

Land

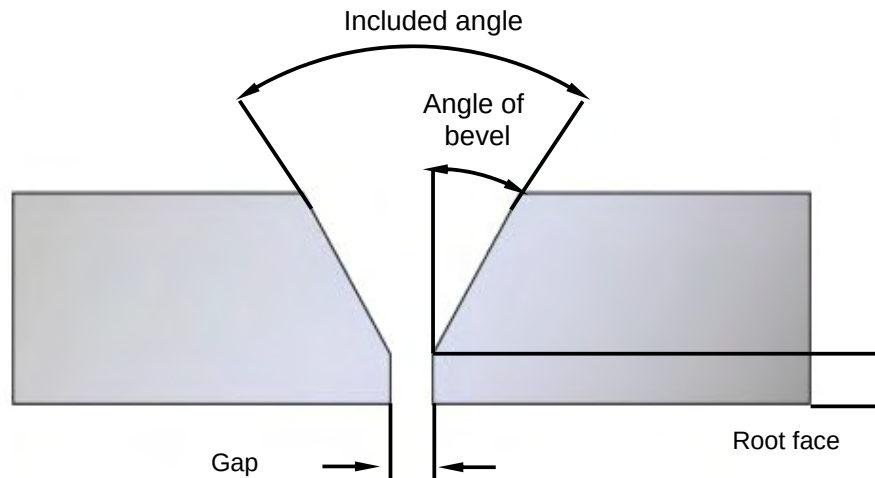
The straight portion of a fusion face between the root face and the curved part of a J or U preparation, can be 0. Usually present in weld preparations for MIG welding of aluminium alloys.

5.2 Types of preparation



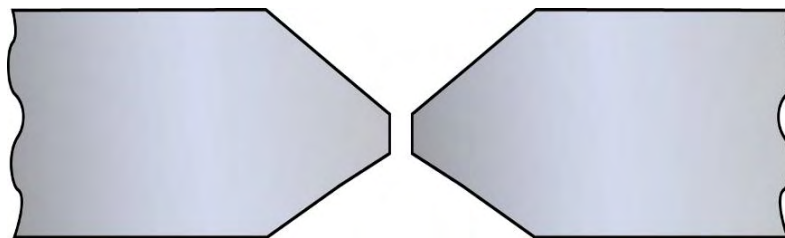
Open square butt preparation

This preparation is used for welding thin components, either from one or both sides. If the root gap is zero (ie if components are in contact), this preparation becomes a closed square butt preparation (not recommended due to the lack of penetration problems)!



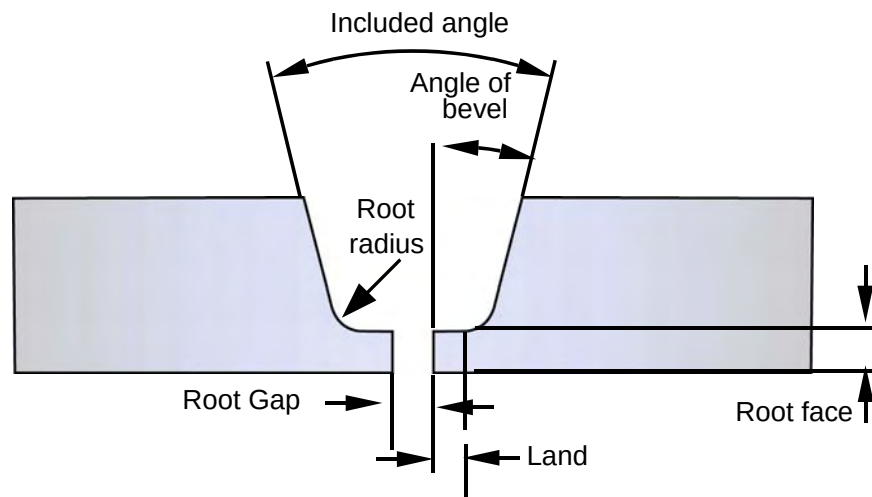
Single V preparation

The V preparation is one of the most common preparations used in welding; it can be produced using flame or plasma cutting (cheap and fast). For thicker plates a double V preparation is preferred since it requires less filler material to complete the joint and the residual stresses can be balanced on both sides of the joint resulting in lower angular distortion.



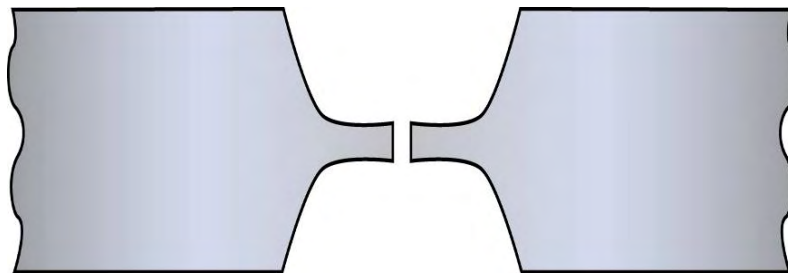
Double V preparation

The depth of preparation can be the same on both sides (symmetric double V preparation) or can be deeper on one side compared with the opposite side (asymmetric double V preparation). Usually, in this situation the depth of preparation is distributed as 2/3 of the thickness of the plate on the first side with the remaining 1/3 on the backside. This asymmetric preparation allows for a balanced welding sequence with root back gouging, giving lower angular distortions. Whilst single V preparation allows welding from one side, double V preparation requires access to both sides (the same applies for all double side preparations).



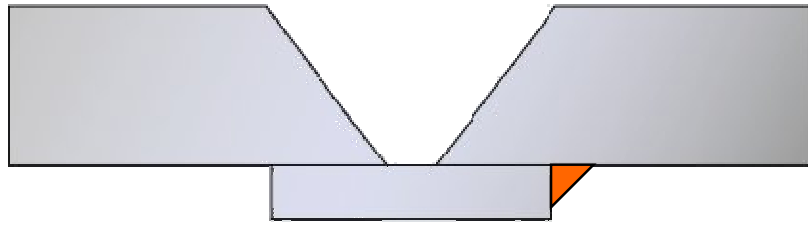
Single U preparation

U preparation can be produced only by machining (slow and expensive). However, tighter tolerances obtained in this case provide for a better fit-up than in the case of V preparations. Usually it is applied to thicker plates compared with single V preparation as it requires less filler material to complete the joint and this leads to lower residual stresses and distortions. Similar to the V preparation, in the case of very thick sections a double U preparation can be used.



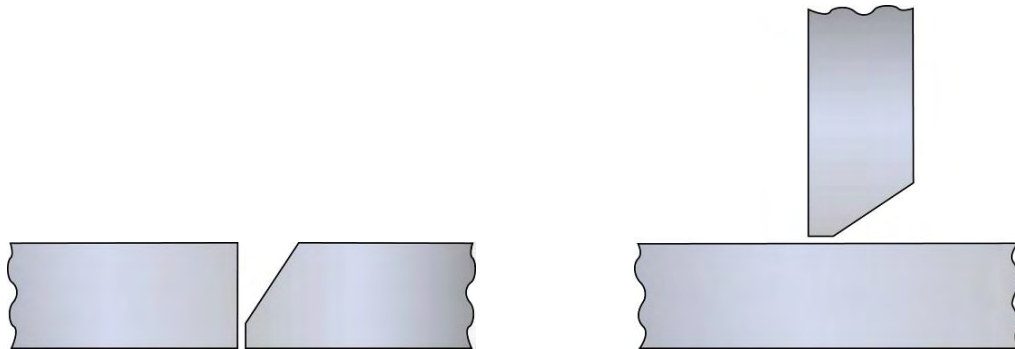
Double U preparation

Usually this type of preparation does not require a land (exception: aluminium alloys).

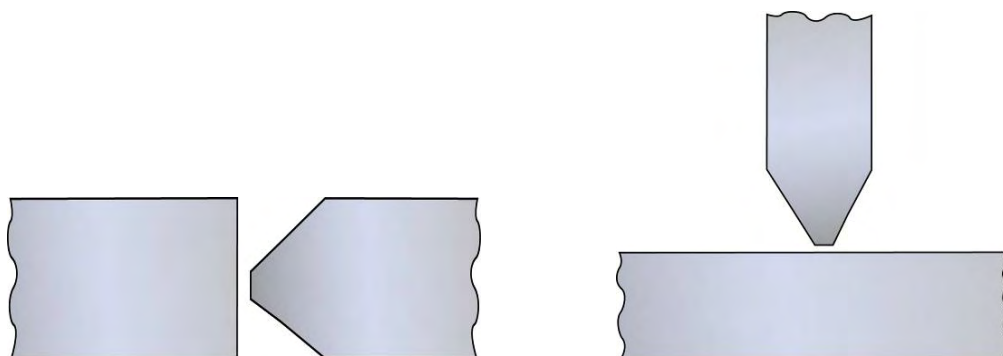


Single V preparation with backing strip

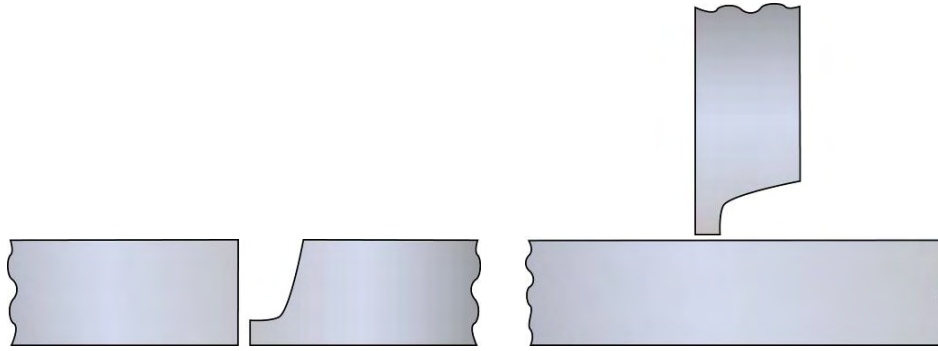
Backing strips allow the production of full penetration welds with increased current and hence increased deposition rates/productivity without the danger of burn-through. Backing strips can be permanent or temporary. Permanent types are made of the same material as being joined and are tack welded in place. The main problems related to this type of weld are poor fatigue resistance and the probability of crevice corrosion between the parent metal and the backing strip. It is also difficult to examine by NDT due to the built-in crevice at the root of the joint. Temporary types include copper strips, ceramic tiles and fluxes.



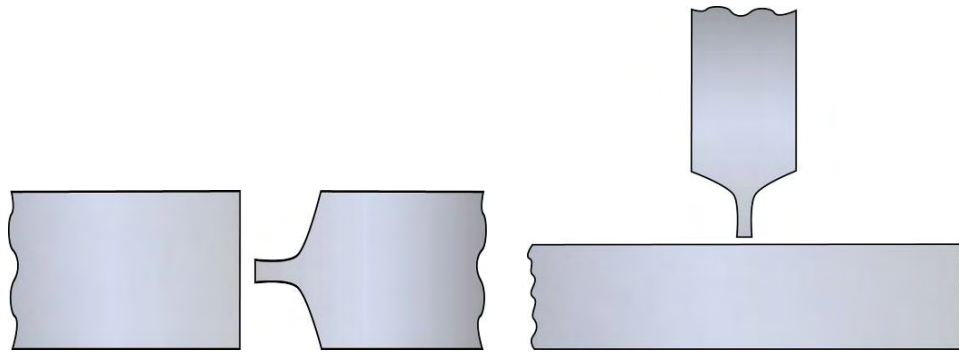
Single bevel preparation



Double bevel preparation



Single J preparation



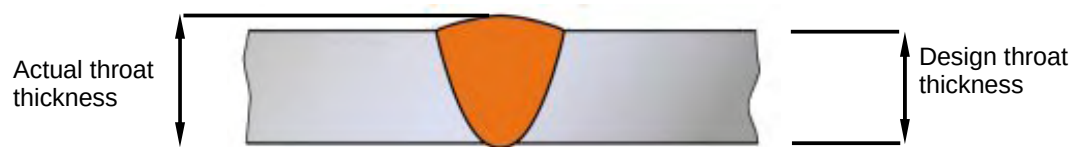
Double J preparation

All these preparations (single/double bevel and J) can be used on T joints as well. Double preparations are recommended in the case of thick sections. The main advantage of these preparations is that only one component is prepared (cheap, can allow for small misalignments).

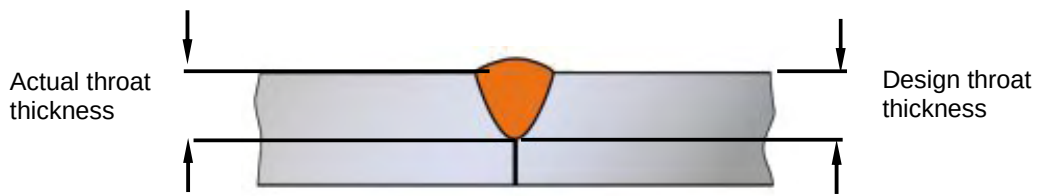
For further details regarding weld preparations, please refer to Standard BS EN ISO 9692.

6 Size of Butt Welds

Full penetration butt weld



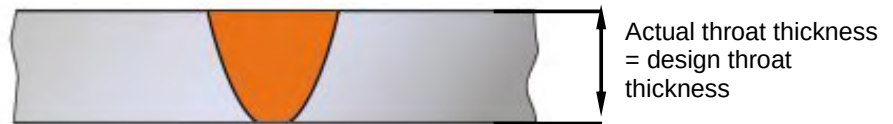
Partial penetration butt weld



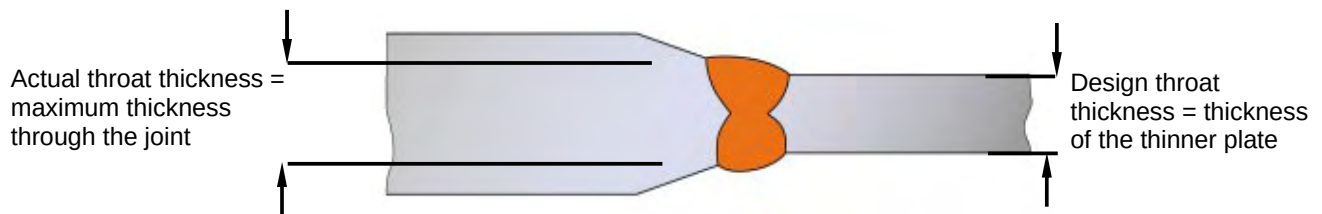
As a general rule:

Actual throat thickness = design throat thickness + excess weld metal .

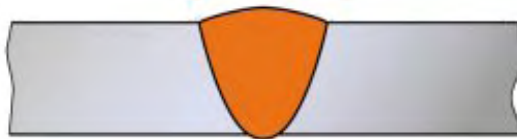
Full penetration butt weld ground flush



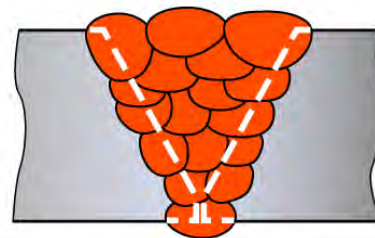
Butt weld between two plates of different thickness



Run (pass): The metal melted or deposited during one passage of an electrode, torch or blowpipe.



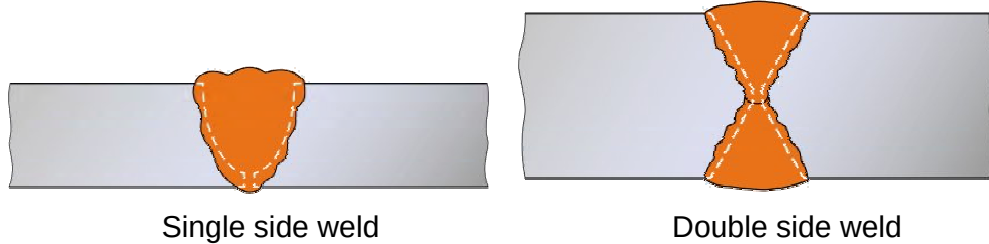
Single run weld



Multi run weld

Layer: A stratum of weld metal consisting of one or more runs.

Types of butt weld (from accessibility point of view):



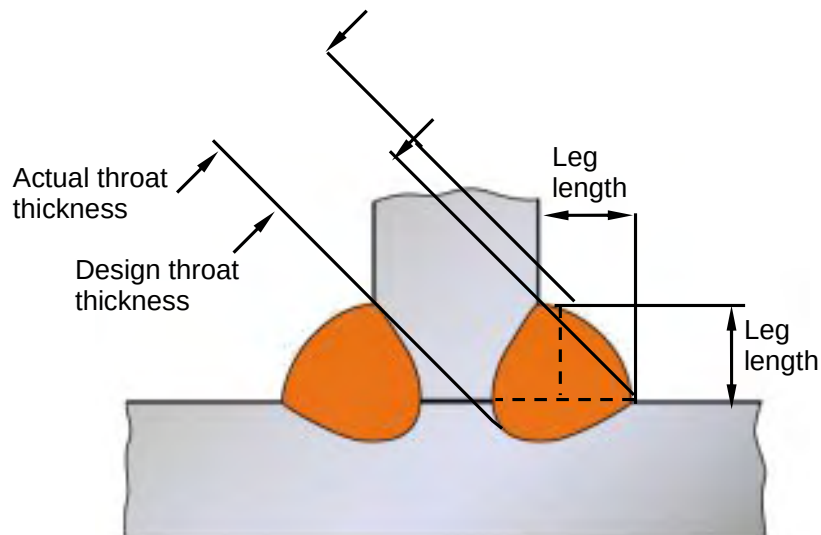
7 Fillet Weld

A fusion weld, other than a butt, edge or fusion spot weld, which is approximately triangular in transverse cross section.

7.1 Size of fillet welds

Unlike butt welds, fillet welds can be defined using several dimensions:

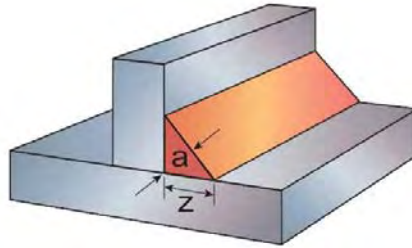
- **Actual throat thickness:** The perpendicular distance between two lines, each parallel to a line joining the outer toes, one being a tangent at the weld face and the other being through the furthestmost point of fusion penetration
- **Design throat thickness:** The minimum dimension of throat thickness used for purposes of design. Also known as effective throat thickness. Symbolised on the drawing with 'a'
- **Leg length:** The distance from the actual or projected intersection of the fusion faces and the toe of a fillet weld, measured across the fusion face. Symbolised on the drawing with 'z'.



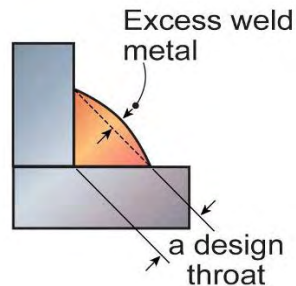
7.2 Shape of fillet welds

Mitre fillet weld: A flat face fillet weld in which the leg lengths are equal within the agreed tolerance. The cross section area of this type of weld can be considered to be a right angle isosceles triangle with a design throat thickness 'a' and leg length 'z'. The relation between design throat thickness and leg length is:

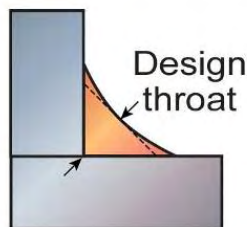
$$a = 0.707 \times z \quad \text{or} \quad z = 1.41 \times a$$



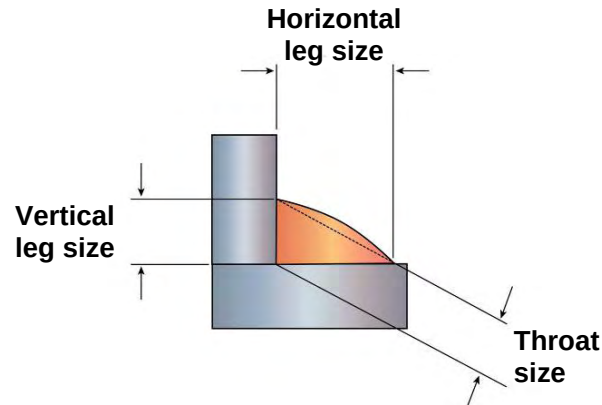
Convex fillet weld: A fillet weld in which the weld face is convex. The above relation between the leg length and the design throat thickness written for mitre fillet welds is also valid for this type of weld. Since there is excess weld metal present in this case, the actual throat thickness is bigger than the design throat thickness.



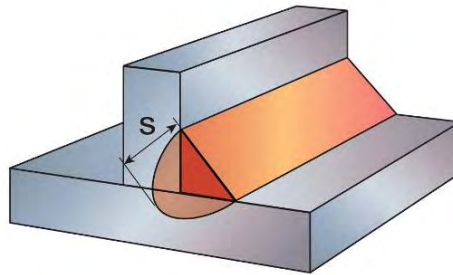
Concave fillet weld: A fillet weld in which the weld face is concave. The relation between the leg length and the design throat thickness specified for mitre fillet welds is not valid for this type of weld. Also, the design throat thickness is equal to the actual throat thickness. Due to the smooth blending between the weld face and the surrounding parent material, the stress concentration effect at the toes of the weld is reduced compared with the previous type. This is why this type of weld is highly desired in case of applications subjected to cyclic loads where fatigue phenomena might be a major cause for failure.



Asymmetrical fillet weld: A fillet weld in which the vertical leg length is not equal to the horizontal leg length. The relation between the leg length and design throat thickness is no longer valid for this type of weld because the cross section is not an isosceles triangle.

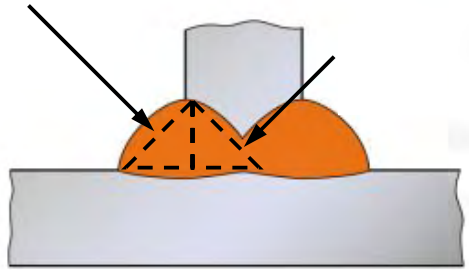


Deep penetration fillet weld: A fillet weld with a deeper than normal penetration. It is produced using high heat input welding processes (ie SAW or MAG with spray transfer). This type of weld uses the benefits of greater arc penetration to obtain the required throat thickness whilst reducing the amount of deposited metal needed, thus leading to a reduction in residual stress level. In order to produce a consistent and constant penetration, the travel speed must be kept constant, at a high value. As a consequence, this type of weld is usually produced using mechanised or automatic welding processes. Also, the high depth-to-width ratio increases the probability of solidification centreline cracking. In order to differentiate this type of weld from the previous types, the throat thickness is symbolised with 's' instead of 'a'.



7.3 Compound of butt and fillet welds

This is a combination of butt and fillet welds used for T joints with full or partial penetration or butt joints between two plates with different thickness. Fillet welds added on top of the groove welds improve the blending of the weld face towards the parent metal surface and reduce the stress concentration at the toes of the weld.

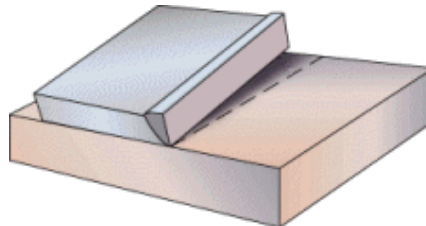


Double bevel compound weld

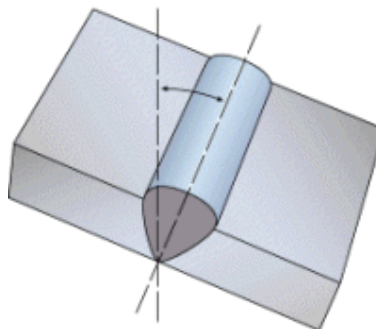
8 Welding Position, Weld Slope and Weld Rotation

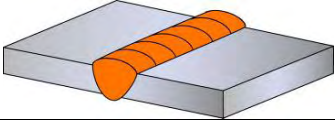
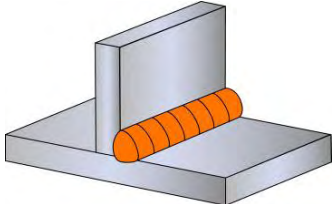
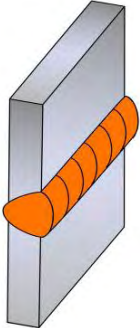
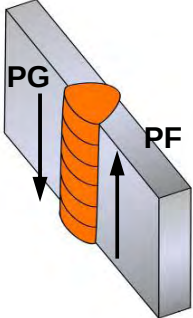
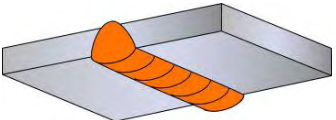
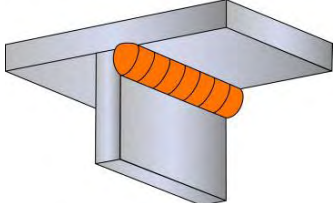
Welding position: The orientation of a weld expressed in terms of working position, weld slope and weld rotation (for further details, please see ISO 6947).

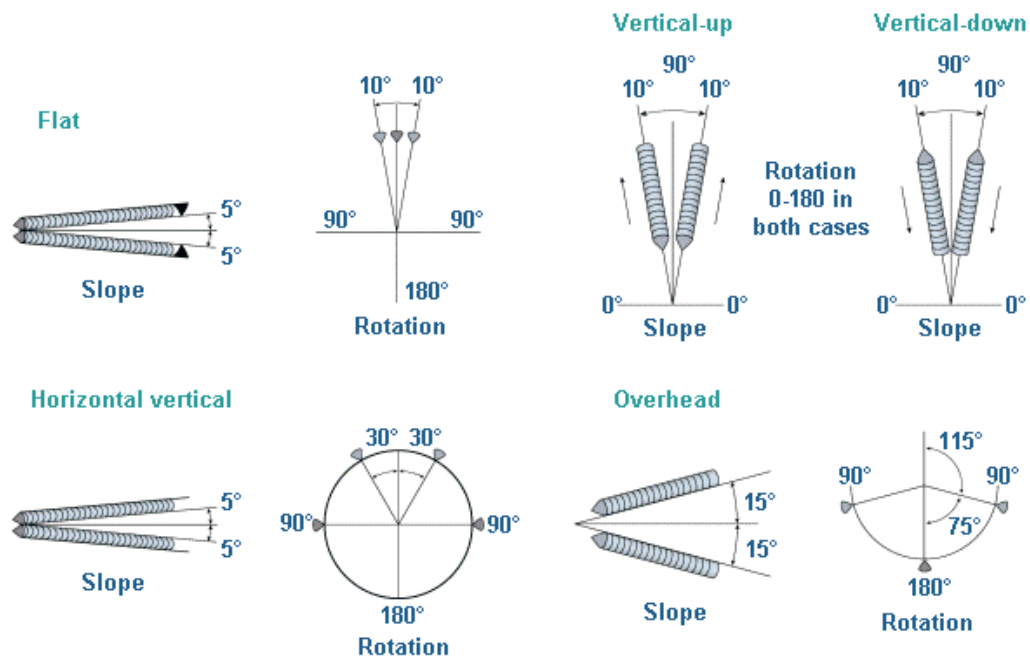
Weld slope: The angle between root line and the positive X axis of the horizontal reference plane, measured in mathematically positive direction (ie counter-clockwise).



Weld rotation: The angle between the centreline of the weld and the positive Z axis or a line parallel to the Y axis, measured in the mathematically positive direction (ie counter-clockwise) in the plane of the transverse cross section of the weld in question.



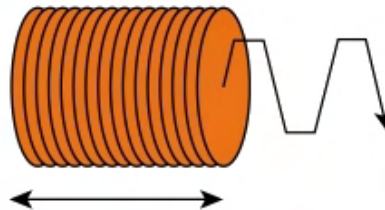
Welding position	Sketch	Definition and symbol according to ISO 6947
Flat		A welding position in which the welding is horizontal, with the centreline of the weld vertical. PA.
Horizontal-vertical		A welding position in which the welding is horizontal (applicable in case of fillet welds). PB
Horizontal		A welding position in which the welding is horizontal, with the centreline of the weld horizontal. PC
Vertical-up		A welding position in which the welding is upwards. PF.
Vertical-down		A welding position in which the welding is downwards. PG
Overhead		A welding position in which the welding is horizontal and overhead, with the centreline of the weld vertical. PE.
Horizontal-overhead		A welding position in which the welding is horizontal and overhead (applicable in case of fillet welds). PD.



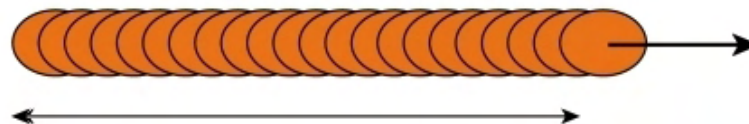
Tolerances for the welding positions

9 Weaving

This is transverse oscillation of an electrode or blowpipe nozzle during the deposition of weld metal. This technique is generally used in vertical-up welds.



Stringer bead: A run of weld metal made with little or no weaving motion.



Welding Imperfections and Materials Inspection

1 Definitions

Definitions: (see BS EN ISO 6520-1)
Imperfection: Any deviation from the ideal weld.
Defect: An unacceptable imperfection.

Classification of imperfections according to BS EN ISO 6520-1:

This standard classifies the geometric imperfections in case of fusion welding, dividing them into six groups:

- 1 Cracks
- 2 Cavities
- 3 Solid inclusions
- 4 Lack of fusion and penetration
- 5 Imperfect shape and dimensions
- 6 Miscellaneous imperfections

It is important that an imperfection is correctly identified thus allowing for the cause to be identified and actions taken to prevent further occurrence.

2 Cracks

Definition: An imperfection produced by a local rupture in the solid state, which may arise from the effect of cooling or stresses. Cracks are more significant than other types of imperfection, as their geometry produces a very large stress concentration at the crack tip, making them more likely to cause fracture.

Types of crack:

- Longitudinal.
- Transverse.
- Radiating (cracks radiating from a common point).
- Crater.
- Branching (group of connected cracks originating from a common crack).

These cracks can be situated in the:

- Weld metal
- HAZ
- Parent metal

Exception: Crater cracks are found only in the weld metal.

Depending on their nature, these cracks can be:

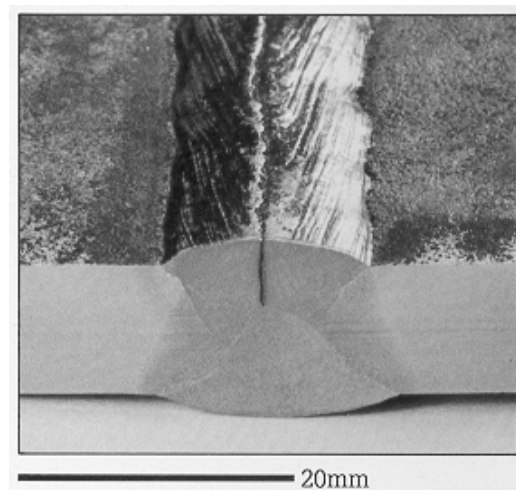
- Hot (ie solidification cracks liquation cracks)
- Precipitation induced (ie reheat cracks, present in creep resisting steels).
- Cold (ie hydrogen induced cracks).
- Lamellar tearing.

2.1 Hot cracks

Depending on their location and mode of occurrence, hot cracks can be:

- Solidification cracks: Occur in the weld metal (usually along the centreline of the weld) as a result of the solidification process
- Liquation cracks: Occur in the coarse grain HAZ, in the near vicinity of the fusion line as a result of heating the material to an elevated temperature, high enough to produce liquation of the low melting point constituents placed on grain boundaries.

2.2 Solidification cracks



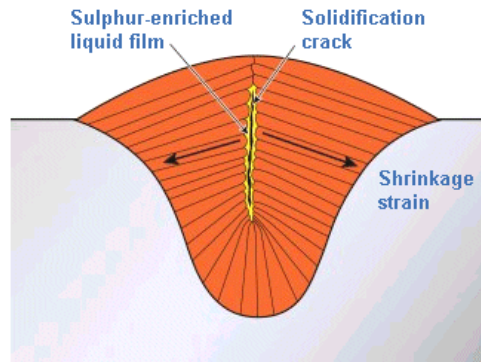
Generally, solidification cracking can occur when:

- The weld metal has a high carbon or impurity (sulphur etc) element content.
- The depth-to-width ratio of the solidifying weld bead is large (deep and narrow).
- Disruption of the heat flow condition occurs, eg stop/start condition

The cracks can be wide and open to the surface like shrinkage voids or sub-surface and possibly narrow.

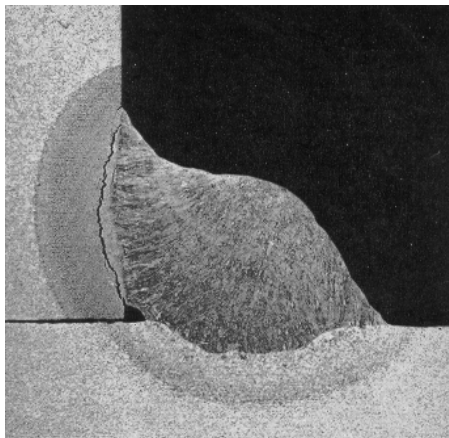
Solidification cracking is most likely to occur in compositions, which result in a wide freezing temperature range. In steels this is commonly created by a higher than normal content of carbon and impurity elements such as sulphur

and phosphorus. These elements segregate during solidification, so that intergranular liquid films remain after the bulk of the weld has solidified. The thermal shrinkage of the cooling weld bead can cause these to rupture and form a crack.

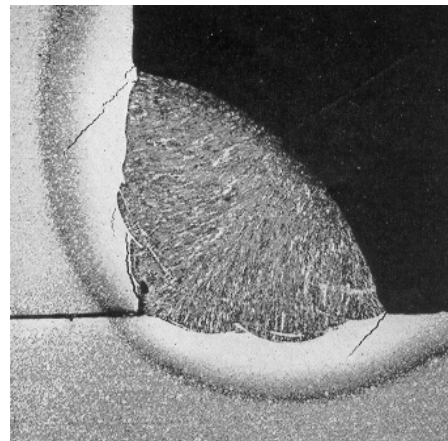


It is important that the welding fabricator does not weld on or near metal surfaces covered with scale or which have been contaminated with oil or grease. Scale can have a high sulphur content, and oil and grease can supply both carbon and sulphur. Contamination with low melting point metals such as copper, tin, lead, and zinc should also be avoided.

2.3 Hydrogen induced cracks



Root (underbead) crack

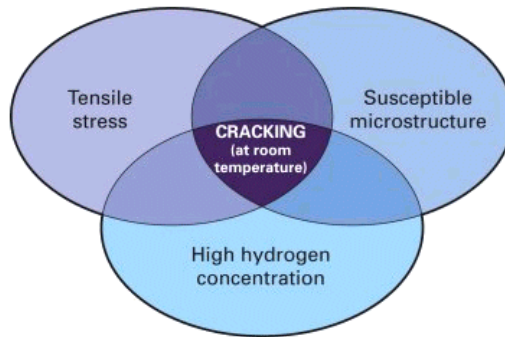


Toe crack

Hydrogen induced cracking occurs primarily in the grain-coarsened region of the HAZ, and is also known as cold, delayed or underbead/toe cracking. Underbead cracking lies parallel to the fusion boundary, and its path is usually a combination of intergranular and transgranular cracking. The direction of the principal residual tensile stress can, for toe cracks, cause the crack path to grow progressively away from the fusion boundary towards a region of lower sensitivity to hydrogen cracking, when this happens, the crack growth rate decreases and eventually arrests.

A combination of four factors is necessary to cause HAZ hydrogen cracking:

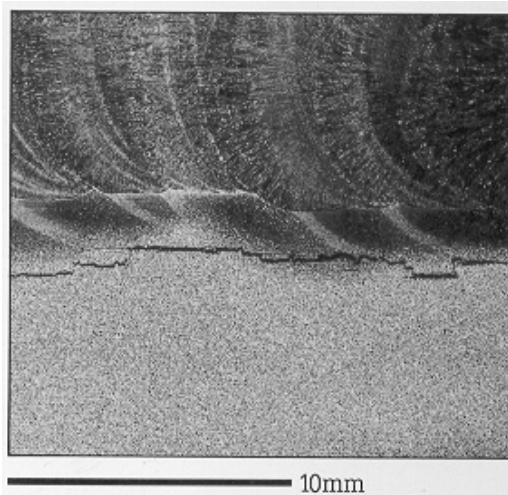
- 1 Hydrogen level > 15ml/100g of weld metal deposited
- 2 Stress > 0.5 of the yield stress
- 3 Temperature < 300°C
- 4 Susceptible microstructure > 400HV hardness



If any one factor is not satisfied, cracking is prevented. Therefore, cracking can be avoided through control of one or more of these factors:

- Apply preheat (to slow down the cooling rate and thus avoid the formation of susceptible microstructures).
- Maintain a specific interpass temperature (same effect as preheat).
- Postheat on completion of welding (to reduce the hydrogen content by allowing hydrogen to effuse from the weld area).
- Apply PWHT (to reduce residual stress and eliminate susceptible microstructures).
- Reduce weld metal hydrogen by proper selection of welding process/consumable (eg use TIG welding instead MMA, use basic covered electrodes instead cellulose ones).
- Use multi- instead of single-run technique (eliminate susceptible microstructures by means of self-tempering effect, reduce the hydrogen content by allowing hydrogen to effuse from the weld area).
- Use a temper bead or hot pass technique (same effect as above).
- Use austenitic or nickel filler (avoid susceptible microstructure formation and allow hydrogen diffusion out of critical areas).
- Use dry shielding gases (reduce hydrogen content).
- Clean rust from joint (avoid hydrogen contamination from moisture present in the rust).
- Reduce residual stress.
- Blend the weld profile (reduce stress concentration at the toes of the weld).

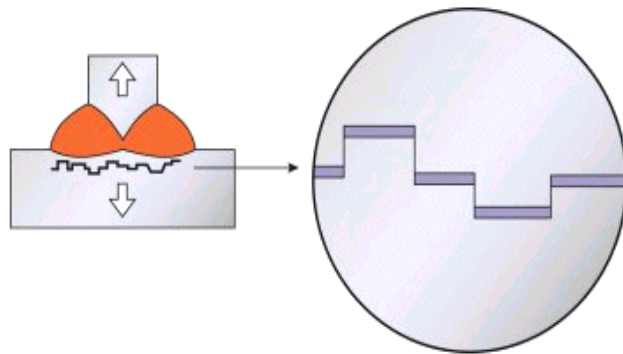
2.4 Lamellar tearing



Lamellar tearing occurs only in rolled steel products (primarily plates) and its main distinguishing feature is that the cracking has a terraced appearance.

Cracking occurs in joints where:

- A thermal contraction strain occurs in the through-thickness direction of steel plate
- Non-metallic inclusions are present as very thin platelets, with their principal planes parallel to the plate surface

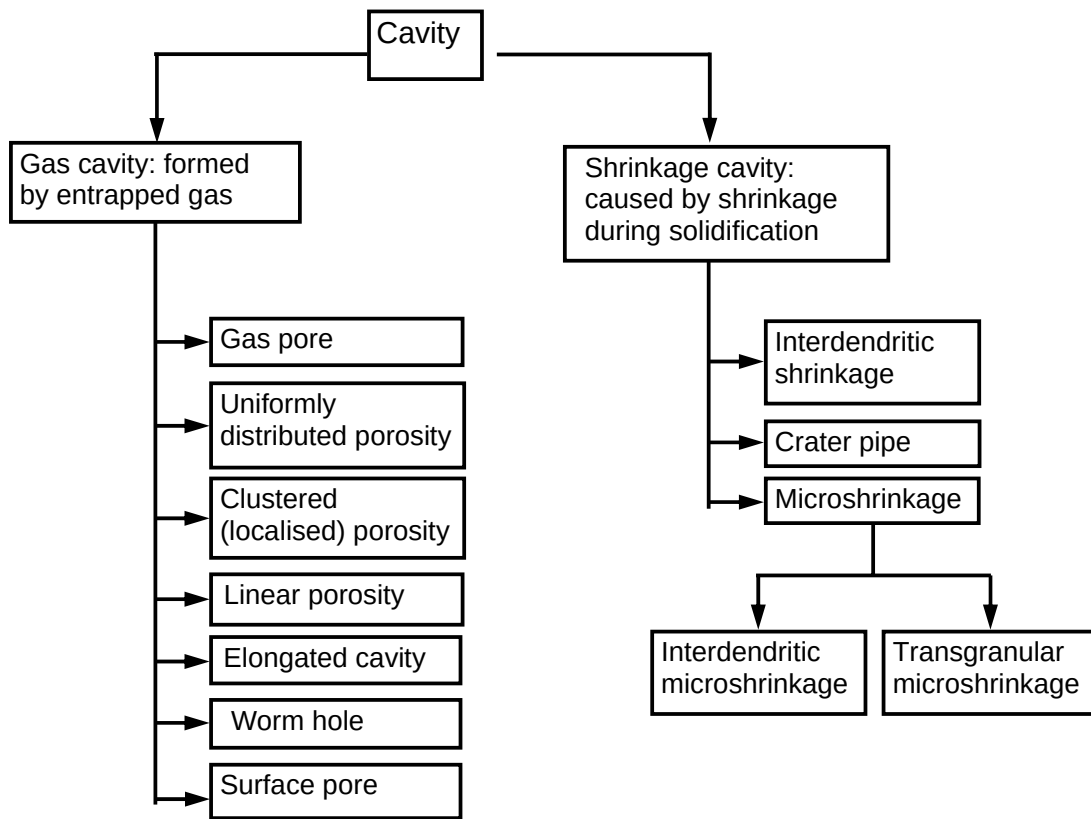


Contraction strain imposed on the planar non-metallic inclusions results in progressive decohesion to form the roughly rectangular holes which are the horizontal parts of the cracking, parallel to the plate surface. With further strain, the vertical parts of the cracking are produced, generally by ductile shear

cracking. These two stages create the terraced appearance of these cracks.

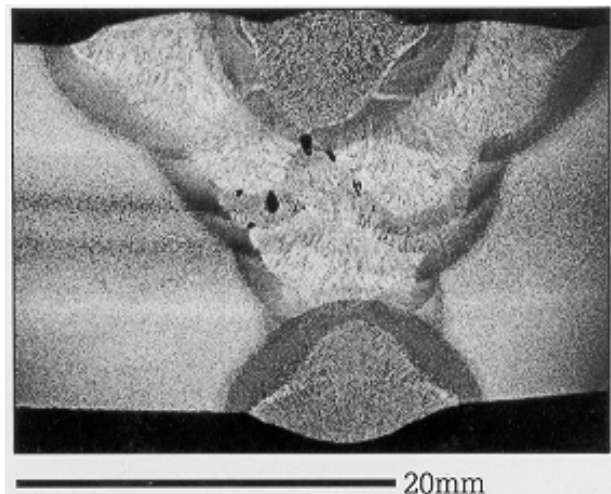
Two main options are available to control the problem in welded joints liable to lamellar tearing:

- Use a clean steel with guaranteed through-thickness properties (Z grade).
- A combination of joint design, restraint control and welding sequence to minimise the risk of cracking.



3 Cavities

3.1 Gas pore



Description

A gas cavity of essentially spherical shape trapped within the weld metal.

Gas cavity can be present in various forms:

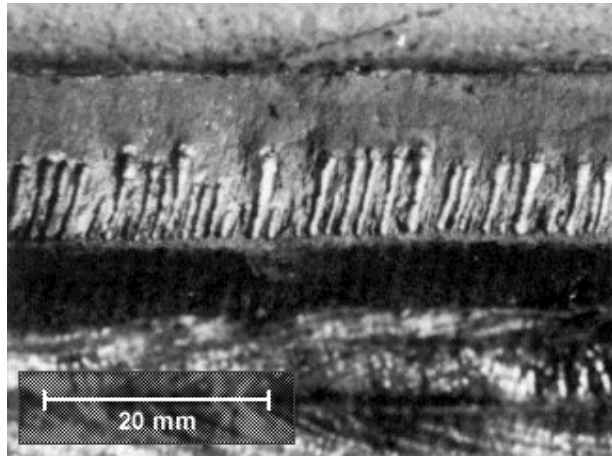
- Isolated
- Uniformly distributed porosity
- Clustered (localised) porosity
- Linear porosity
- Elongated cavity
- Surface pore

Causes	Prevention
Damp fluxes/corroded electrode (MMA)	Use dry electrodes in good condition
Grease/hydrocarbon/water contamination of prepared surface	Clean prepared surface
Air entrapment in gas shield (MIG/MAG, TIG)	Check hose connections
Incorrect/insufficient deoxidant in electrode, filler or parent metal	Use electrode with sufficient deoxidation activity
Too high an arc voltage or length	Reduce voltage and arc length
Gas evolution from priming paints/surface treatment	Identify risk of reaction before surface treatment is applied
Too high a shielding gas flow rate which results in turbulence (MIG/MAG, TIG)	Optimise gas flow rate

Comments

Note that porosity can either be localised or finely dispersed voids throughout the weld metal.

3.2 Worm holes



Description

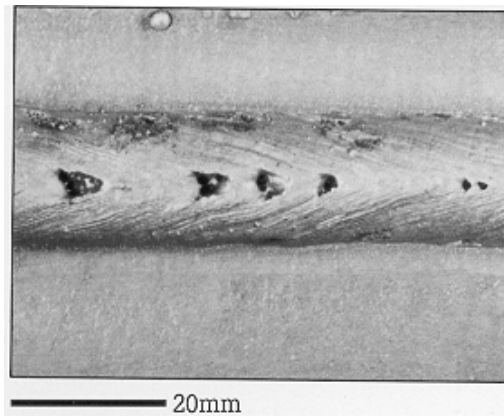
Elongated or tubular cavities formed by entrapped gas during the solidification of the weld metal; they can occur singly or in groups.

Causes	Prevention
Gross contamination of preparation surface	Introduce preweld cleaning procedures
Laminated work surface	Replace parent material with an unlaminated piece
Crevices in work surface due to joint geometry	Eliminate joint shapes which produce crevices

Comments

Worm holes are caused by the progressive entrapment of gas between the solidifying metal crystals (dendrites) producing characteristic elongated pores of circular cross-section. These elongated pores can appear as a herring-bone array on a radiograph. Some of them may break the surface of the weld.

3.3 Surface porosity



Description

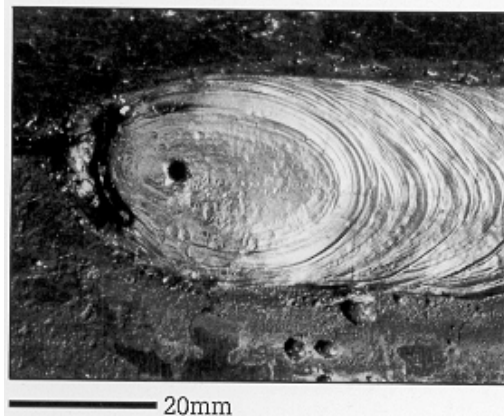
A gas pore that breaks the surface of the weld.

Causes	Prevention
Damp or contaminated surface or electrode	Clean surface and dry electrodes
Low fluxing activity (MIG/MAG)	Use a high activity flux
Excess sulphur (particularly free-cutting steels) producing sulphur dioxide	Use high manganese electrode to produce MnS, note free-cutting steels (high sulphur) should not normally be welded
Loss of shielding gas due to long arc or high breezes (MIG/MAG)	Improve screening against draughts and reduce arc length
Too high a shielding gas flow rate which results in turbulence (MIG/MAG, TIG)	Optimise gas flow rate

Comments

The origins of surface porosity are similar to those for uniform porosity.

3.4 Crater pipe



Description

A shrinkage cavity at the end of a weld run. The main cause is shrinkage during solidification.

Causes	Prevention
Lack of welder skill due to using processes with too high a current	Retrain welder
Inoperative crater filler (slope out) (TIG)	Use correct crater filling techniques

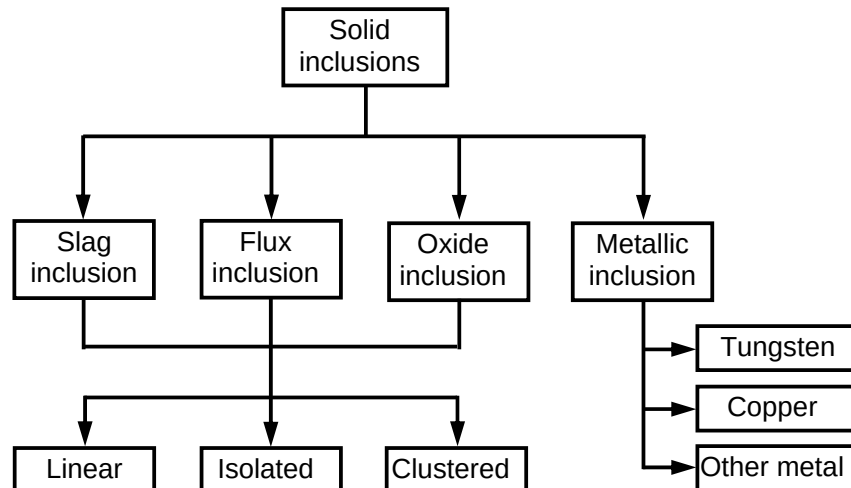
Comments

Crater filling is a particular problem in TIG welding due to its low heat input. To fill the crater for this process it is necessary to reduce the weld current (slope out) in a series of descending steps until the arc is extinguished.

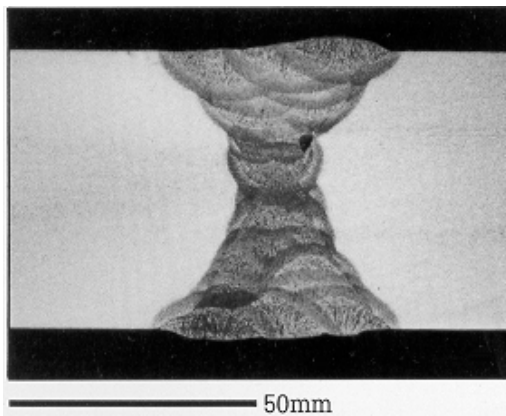
4 Solid Inclusions

Definition

Solid foreign substances entrapped in the weld metal.



4.1 Slag inclusions



Description

Slag trapped during welding. The imperfection is an irregular shape and thus differs in appearance from a gas pore.

Causes	Prevention
Incomplete slag removal from underlying surface of multipass weld	Improve inter-run slag removal
Slag flooding ahead of arc	Position work to gain control of slag. Welder needs to correct electrode angle
Entrapment of slag in work surface	Dress/make work surface smooth

Comments

A fine dispersion of inclusions may be present within the weld metal, particularly if the MMA process is used. These only become a problem when large or sharp-edged inclusions are produced.

4.2 Flux inclusions

Description

Flux trapped during welding. The imperfection is of an irregular shape and thus differs in appearance from a gas pore. Appear only in case of flux associated welding processes (ie MMA, SAW and FCAW).

Causes	Prevention
Unfused flux due to damaged coating	Use electrodes in good condition
Flux fails to melt and becomes trapped in the weld (SAW or FCAW)	Change the flux/wire. Adjust welding parameters ie current, voltage etc to produce satisfactory welding conditions

4.3 Oxide inclusions

Description

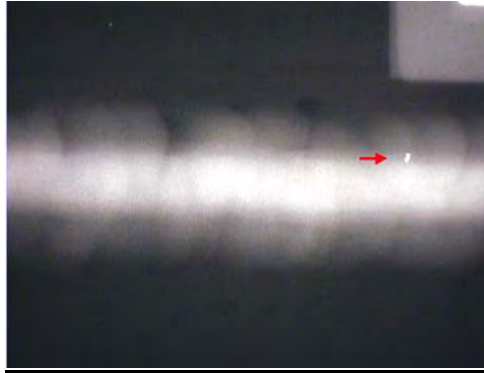
Oxides trapped during welding. The imperfection is of an irregular shape and thus differs in appearance from a gas pore.

Cause	Prevention
Heavy mill scale/rust on work surface	Grind surface prior to welding

Comments

A special type of oxide inclusion is puckering. This type of defect occurs especially in the case of aluminium alloys. Gross oxide film enfoldment can occur due to a combination of unsatisfactory protection from atmospheric contamination and turbulence in the weld pool.

4.4 Tungsten inclusions



Description

Particles of tungsten can become embedded during TIG welding. This imperfection appears as a light area on radiographs due to the fact that tungsten is denser than the surrounding metal and absorbs larger amounts of X-/gamma radiation.

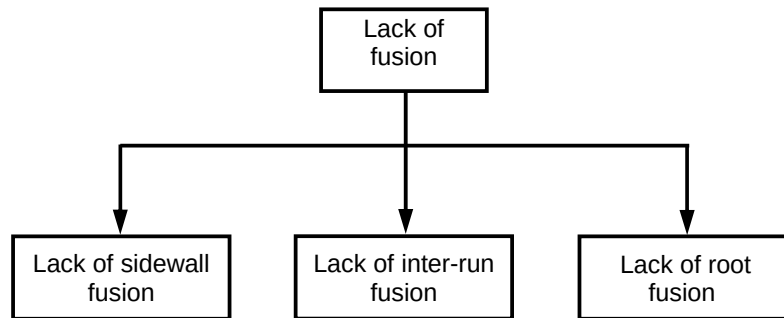
Causes	Prevention
Contact of electrode tip with weld pool	Keep tungsten out of weld pool; use HF start
Contact of filler metal with hot tip of electrode	Avoid contact between electrode and filler metal
Contamination of the electrode tip by spatter from the weld pool	Reduce welding current; adjust shielding gas flow rate
Exceeding the current limit for a given electrode size or type	Reduce welding current; replace electrode with a larger diameter one
Extension of electrode beyond the normal distance from the collet, resulting in overheating of the electrode	Reduce electrode extension and/or welding current
Inadequate tightening of the collet	Tighten the collet
Inadequate shielding gas flow rate or excessive wind draughts resulting in oxidation of the electrode tip	Adjust the shielding gas flow rate; protect the weld area; ensure that the post gas flow after stopping the arc continues for at least 5 seconds
Splits or cracks in the electrode	Change the electrode, ensure the correct size tungsten is selected for the given welding current used
Inadequate shielding gas (eg use of argon-oxygen or argon-carbon dioxide mixtures that are used for MAG welding)	Change to correct gas composition

5 Lack of Fusion and Penetration

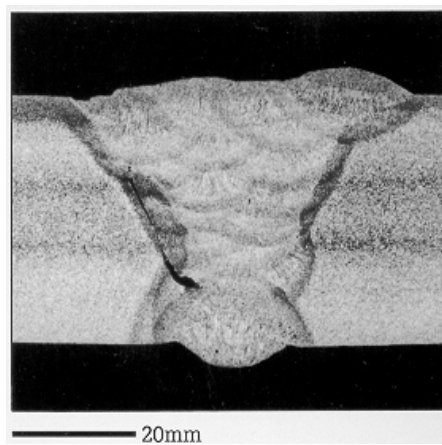
5.1 Lack of fusion

Definition

Lack of union between the weld metal and the parent metal or between the successive layers of weld metal.



5.1.1 Lack of sidewall fusion



Description

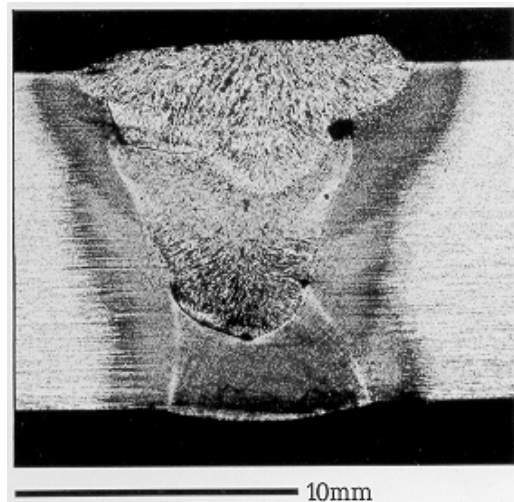
Lack of union between the weld and parent metal at one or both sides of the weld.

Causes	Prevention
Low heat input to weld	Increase arc voltage and/or welding current; decrease travel speed
Molten metal flooding ahead of arc	Improve electrode angle and work position; increase travel speed
Oxide or scale on weld preparation	Improve edge preparation procedure
Excessive inductance in MAG dip transfer welding	Reduce inductance, even if this increases spatter

Comments

During welding sufficient heat must be available at the edge of the weld pool to produce fusion with the parent metal.

5.1.2 Lack of inter-run fusion



Description

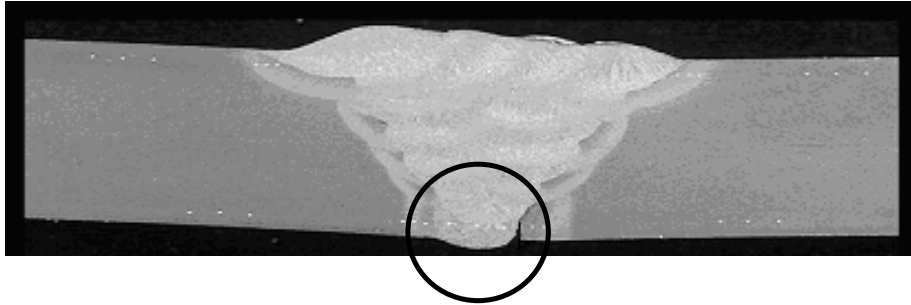
A lack of union along the fusion line, between the weld beads.

Causes	Prevention
Low arc current resulting in low fluidity of weld pool	Increase current
Too high a travel speed	Reduce travel speed
Inaccurate bead placement	Retrain welder

Comments

Lack of inter-run fusion produces crevices between the weld beads and causes local entrapment of slag.

5.1.3 Lack of root fusion

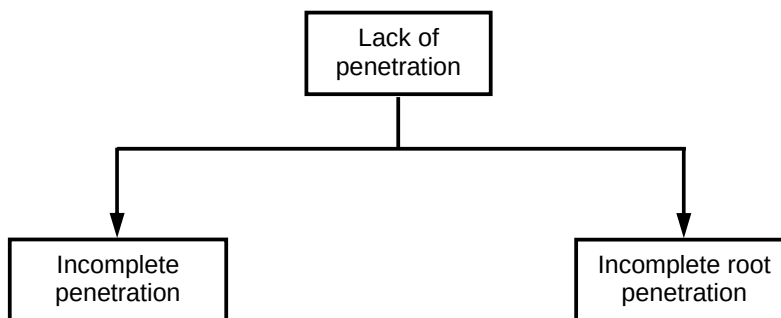


Description

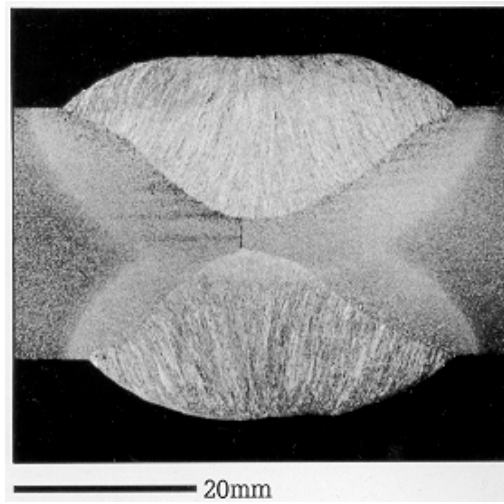
Lack of fusion between the weld and parent metal at the root of a weld.

Causes	Prevention
Low heat input	Increase welding current and/or arc voltage; decrease travel speed
Excessive inductance in MAG dip transfer welding,	Use correct induction setting for the parent metal thickness
MMA electrode too large (low current density)	Reduce electrode size
Use of vertical down welding	Switch to vertical up procedure
Large root face	Reduce root face
Small root gap	Ensure correct root opening
Incorrect angle or incorrect electrode manipulation	Use correct electrode angle. Ensure welder is fully qualified and competent
Excessive misalignment at root	Ensure correct alignment

5.2 Lack of penetration



5.2.1 Incomplete penetration



Description

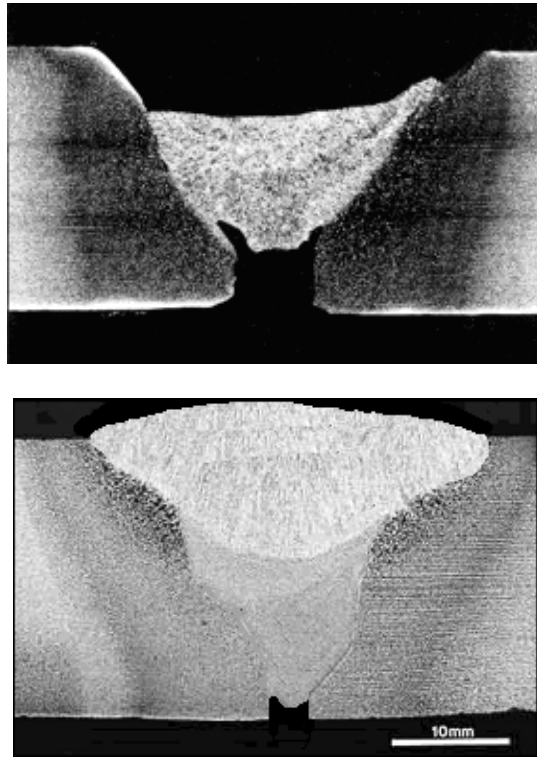
The difference between actual and nominal penetration.

Causes	Prevention
Excessively thick root face, insufficient root gap or failure to cut back to sound metal in a 'back gouging' operation	Improve back gouging technique and ensure the edge preparation is as per approved WPS
Low heat input	Increase welding current and/or arc voltage; decrease travel speed
Excessive inductance in MAG dip transfer welding, pool flooding ahead of arc	Improve electrical settings and possibly switch to spray arc transfer
MMA electrode too large (low current density)	Reduce electrode size
Use of vertical down welding	Switch to vertical up procedure

Comments

If the weld joint is not of a critical nature, ie the required strength is low and the area is not prone to fatigue cracking, it is possible to produce a partial penetration weld. In this case incomplete root penetration is considered part of this structure and is not an imperfection (this would normally be determined by the design or code requirement).

5.2.2 Incomplete root penetration



Description

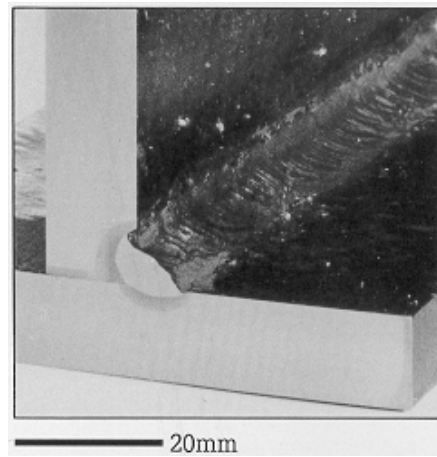
One or both fusion faces of the root are not melted. When examined from the root side, you can clearly see one or both of the root edges unmelted.

Causes and prevention

Same as for lack of root fusion.

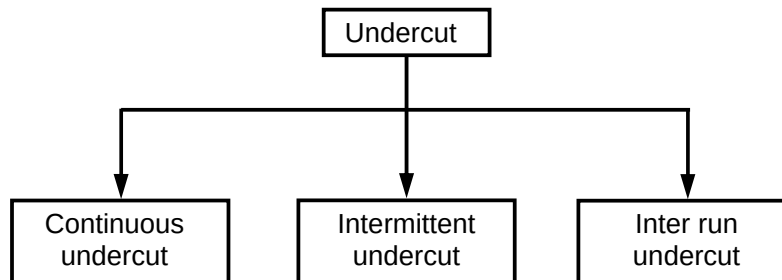
6 Imperfect Shape and Dimensions

6.1 Undercut



Description

An irregular groove at the toe of a run in the parent metal or in a previously deposited weld metal due to welding. It is characterised by its depth, length and sharpness.

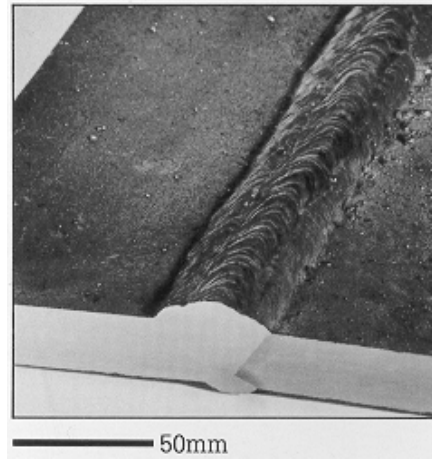


Causes	Prevention
Melting of top edge due to high welding current (especially at free edge) or high travel speed	Reduce power input, especially approaching a free edge where overheating can occur
Attempting a fillet weld in horizontal vertical (PB) position with leg length >9mm	Weld in the flat position or use multi-run techniques
Excessive/incorrect weaving	Reduce weaving width or switch to multi-runs
Incorrect electrode angle	Direct arc towards thicker member
Incorrect shielding gas selection (MAG)	Ensure correct gas mixture for material type and thickness (MAG)

Comments

Care must be taken during weld repairs of undercut to control the heat input. If the bead of a repair weld is too small, the cooling rate following welding will be excessive and the parent metal may have an increased hardness and the weld may be susceptible to hydrogen cracking.

6.2 Excess weld metal



Description

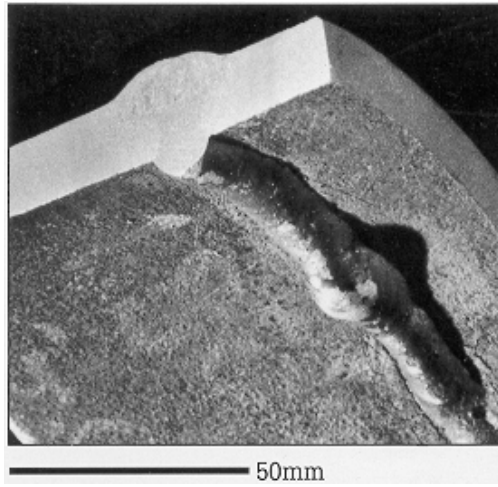
Excess weld metal is the extra metal that produces excessive convexity in fillet welds and a weld thickness greater than the parent metal plate in butt welds. This feature of a weld is regarded as an imperfection only when the height of the excess weld metal is greater than a specified limit.

Causes	Prevention
Excess arc energy (MAG, SAW)	Reduction of heat input
Shallow edge preparation	Deepen edge preparation
Faulty electrode manipulation or build-up sequence	Improve welder skill
Incorrect electrode size	Reduce electrode size
Too slow a travel speed	Ensure correct travel speed is used
Incorrect electrode angle	Ensure correct electrode angle is used
Wrong polarity used (electrode polarity DC-VE (MMA, SAW)	Ensure correct polarity ie DC +VE Note DC-VE must be used for TIG

Comments

The term 'reinforcement' used to designate this feature of the weld is misleading since the excess metal does not normally produce a stronger weld in a butt joint in ordinary steel. This imperfection can become a problem, as the angle of the weld toe can be sharp, leading to an increased stress concentration at the toes of the weld and fatigue cracking.

6.3 Excess penetration



Description

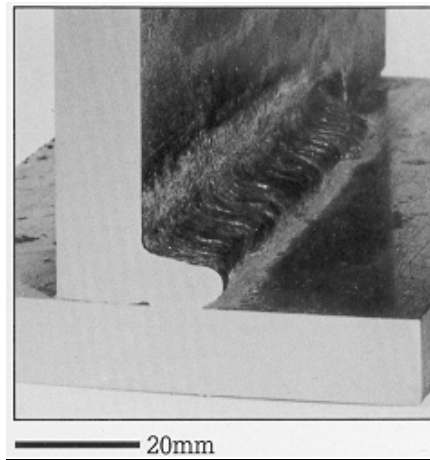
Projection of the root penetration bead beyond a specified limit can be local or continuous.

Causes	Prevention
Weld heat input too high	Reduce arc voltage and/or welding current; increase welding speed
Incorrect weld preparation ie excessive root gap, thin edge preparation, lack of backing	Improve workpiece preparation
Use of electrode unsuited to welding position	Use correct electrode for position
Lack of welder skill	Retrain welder

Comments

Note that the maintenance of a penetration bead having uniform dimensions requires a great deal of skill, particularly in pipe butt welding. This can be made more difficult if there is restricted access to the weld or a narrow preparation. Permanent or temporary backing bars can be used to assist in the control of penetration.

6.4 Overlap



Description

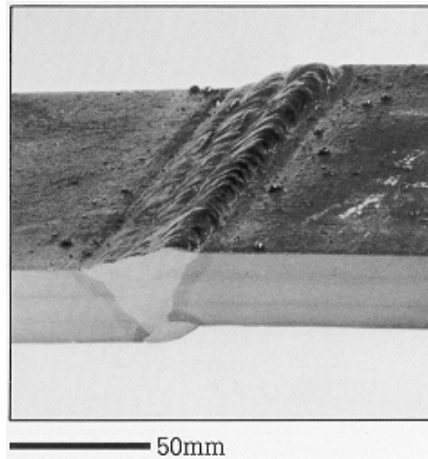
An imperfection at the toe of a weld caused by metal flowing on to the surface of the parent metal without fusing to it.

Causes	Prevention
Poor electrode manipulation (MMA)	Retrain welder
High heat input/low travel speed causing surface flow of fillet welds	Reduce heat input or limit leg size to 9mm max leg size for single pass fillets.
Incorrect positioning of weld	Change to flat position
Wrong electrode coating type resulting in too high a fluidity	Change electrode coating type to a more suitable fast freezing type which is less fluid

Comments

For a fillet weld overlap is often associated with undercut, as if the weld pool is too fluid the top of the weld will flow away to produce undercut at the top and overlap at the base. If the volume of the weld pool is too large in case of a fillet weld in horizontal-vertical (PB) position, weld metal will collapse due to gravity, producing both defects (undercut at the top and overlap at the base), this defect is called 'sagging'.

6.5 Linear misalignment



Description

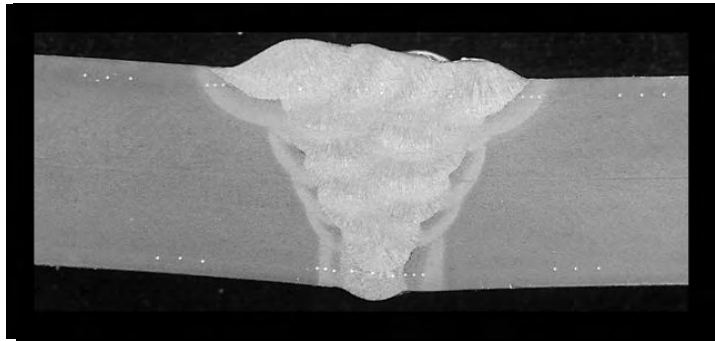
Misalignment between two welded pieces such that while their surface planes are parallel, they are not in the required same plane.

Causes	Prevention
Inaccuracies in assembly procedures or distortion from other welds	Adequate checking of alignment prior to welding coupled with the use of clamps and wedges
Excessive out of flatness in hot rolled plates or sections	Check accuracy of rolled section prior to welding

Comments

Misalignment is not really a weld imperfection, but a structural preparation problem. Even a small amount of misalignment can drastically increase the local shear stress at a joint and induce bending stress.

6.6 Angular distortion



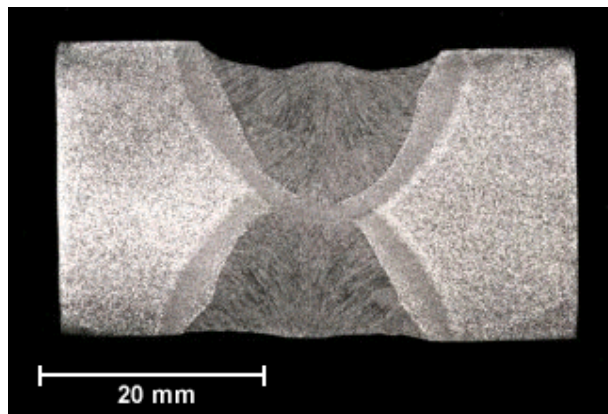
Description

Misalignment between two welded pieces such that their surface planes are not parallel or at the intended angle.

Causes and prevention

Same as for linear misalignment.

6.7 Incompletely filled groove



Description

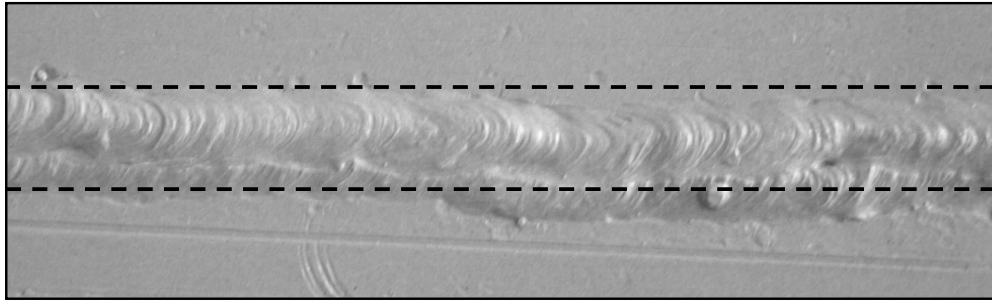
A continuous or intermittent channel in the surface of a weld due to insufficient deposition of weld filler metal.

Causes	Prevention
Insufficient weld metal	Increase the number of weld runs
Irregular weld bead surface	Retrain welder

Comments

This imperfection differs from undercut, it reduces the load-bearing capacity of a weld, whereas undercut produces a sharp stress-raising notch at the edge of a weld.

6.8 Irregular width



Description

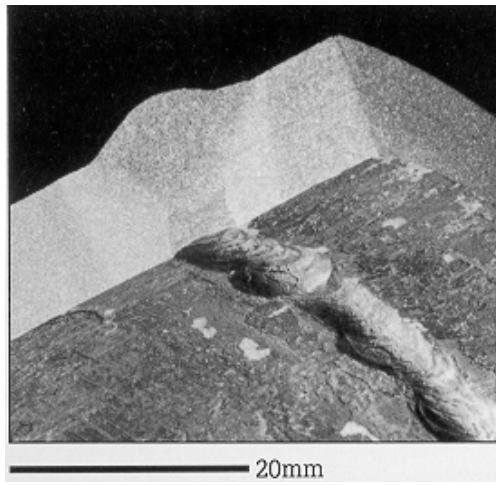
Excessive variation in width of the weld.

Causes	Prevention
Severe arc blow	Switch from DC to AC, keep as short as possible arc length
Irregular weld bead surface	Retrain welder

Comments

Although this imperfection may not affect the integrity of completed weld, it can affect the width of HAZ and reduce the load-carrying capacity of the joint (in the case of fine-grained structural steels) or impair corrosion resistance (in the case of duplex stainless steels).

6.9 Root concavity



Description

A shallow groove that occurs due to shrinkage at the root of a butt weld.

Causes	Prevention
Insufficient arc power to produce positive bead	Raise arc energy
Incorrect prep/fit-up	Work to WPS
Excessive backing gas pressure (TIG)	Reduce gas pressure
Lack of welder skill	Retrain welder
Slag flooding in backing bar groove	Tilt work to prevent slag flooding

Comments

A backing strip can be used to control the extent of the root bead.

6.10 Burn-through



Description

A collapse of the weld pool resulting in a hole in the weld.

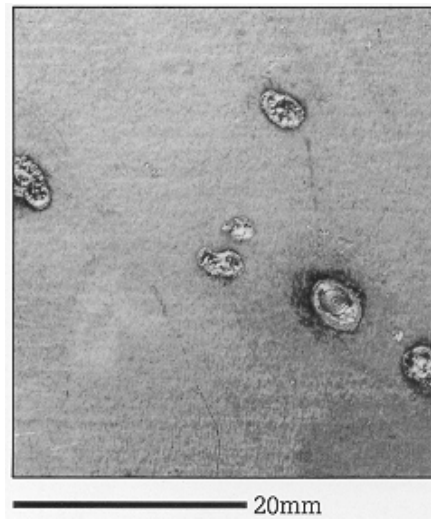
Causes	Prevention
Insufficient travel speed	Increase the travel speed
Excessive welding current	Reduce welding current
Lack of welder skill	Retrain welder
Excessive grinding of root face	More care taken, retrain welder
Excessive root gap	Ensure correct fit-up

Comments

This is a gross imperfection, which occurs basically due to lack of welder skill. It can be repaired by bridging the gap formed into the joint, but requires a great deal of attention.

7 Miscellaneous Imperfections

7.1 Stray arc



Description

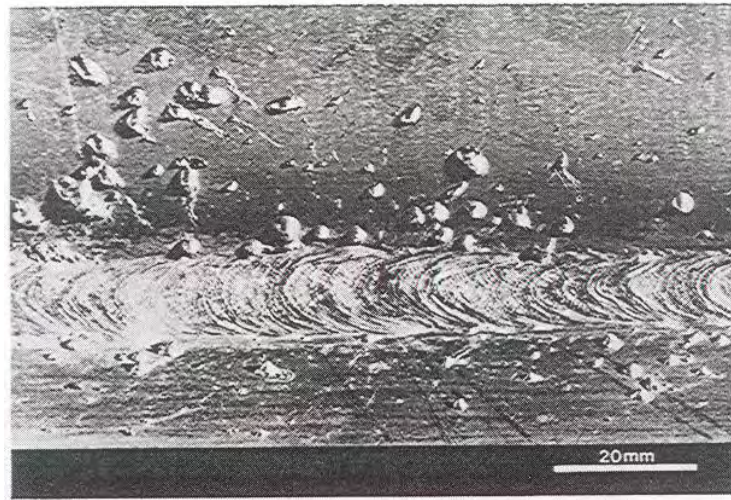
Local damage to the surface of the parent metal adjacent to the weld, resulting from arcing or striking the arc outside the weld groove. This results in random areas of fused metal where the electrode, holder, or current return clamp have accidentally touched the work.

Causes	Prevention
Poor access to the work	Improve access (modify assembly sequence)
Missing insulation on electrode holder or torch	Institute a regular inspection scheme for electrode holders and torches
Failure to provide an insulated resting place for the electrode holder or torch when not in use	Provide an insulated resting place
Loose current return clamp	Regularly maintain current return clamps
Adjusting wire feed (MAG welding) without isolating welding current	Retrain welder

Comments

An arc strike can produce a hard HAZ, which may contain cracks. These can lead to serious cracking in service. It is better to remove an arc strike by grinding than weld repair.

7.2 Spatter



Description

Globules of weld or filler metal expelled during welding and adhering to the surface of parent metal or solidified weld metal.

Causes	Prevention
High arc current	Reduce arc current
Long arc length	Reduce arc length
Magnetic arc blow	Reduce arc length or switch to AC power
Incorrect settings for GMAW process	Modify electrical settings (but be careful to maintain full fusion!)
Damp electrodes	Use dry electrodes
Wrong selection of shielding gas (100%CO ₂)	Increase argon content if possible, however too high a % may lead to lack of penetration

Comments

Spatter in itself is a cosmetic imperfection and does not affect the integrity of the weld. However as it is usually caused by an excessive welding current, it is a sign that the welding conditions are not ideal and so there are usually other associated problems within the structure ie high heat input. Note that some spatter is always produced by open arc consumable electrode welding processes. Anti-spatter compounds can be used on the parent metal to reduce sticking and the spatter can then be scraped off.

7.3 Torn surface

Description

Surface damage due to the removal by fracture of temporary welded attachments. The area should be ground off, then subjected to a dye penetrant or magnetic particle examination and then restored to its original shape by welding using a qualified procedure. NOTE: Some applications do not allow the presence of any overlay weld on the surface of the parent material.

7.4 Additional imperfections

Grinding mark

Description

Local damage due to grinding.

Chipping mark

Description

Local damage due to the use of a chisel or other tools.

Underflushing

Description

Lack of thickness of the workpiece due to excessive grinding.

Misalignment of opposite runs

Description

Difference between the centrelines of two runs made from opposite sides of the joint.

Temper colour (visible oxide film)

Description

Lightly oxidised surface in the weld zone, usually occurs in stainless steels.



8 Acceptance Standards

Weld imperfections can seriously reduce the integrity of a welded structure. Therefore, prior to service of a welded joint, it is necessary to locate them using NDE techniques, assess their significance, and take action to avoid their reoccurrence.

The acceptance of a certain size and type of defect for a given structure is normally expressed as the defect acceptance standard. This is usually incorporated in application standards or specifications.

All normal weld imperfection acceptance standards totally reject cracks. However, in exceptional circumstances, and subject to the agreement of all parties, cracks may be allowed to remain if it can be demonstrated beyond doubt that they will not lead to failure. This can be difficult to establish and usually involves fracture mechanics measurements and calculations.

It is important to note that the levels of acceptability vary between different applications, and in most cases vary between different standards for the same application. Consequently, when inspecting different jobs it is important to use the applicable standard or specification quoted in the contract.

Once unacceptable weld imperfections have been found, they have to be removed. If the weld imperfection is at the surface, the first consideration is whether it is of a type, which is normally shallow enough to be repaired by superficial dressing. Superficial implies that, after removal of the defect, the remaining material thickness is sufficient not to require the addition of further weld metal.

If the defect is too deep, it must be removed and new weld metal added to ensure a minimum design throat thickness.

Replacing removed metal or weld repair (as in filling an excavation or re-making a weld joint) has to be done in accordance with an approved procedure. The rigour with which this procedure is qualified will depend on the application standard for the job. In some cases it will be acceptable to use a procedure qualified for making new joints whether filling an excavation or making a complete joint. If the level of reassurance required is higher, the qualification will have to be made using an exact simulation of a welded joint, which is excavated and then refilled using a specified method. In either case, qualification inspection and testing will be required in accordance with the application standard.

1 Introduction

European Welding Standards require test coupons that are made for welding procedure qualification testing to be subjected to non-destructive and then destructive testing.

The tests are called destructive tests because the welded joint is destroyed when various types of test piece are taken from it.

Destructive tests can be divided into two groups, those used to:

- Measure a mechanical property – **quantitative tests**
- Assess the joint quality – **qualitative tests**

Mechanical tests are quantitative because a quantity is measured – a mechanical property such as tensile strength, hardness or impact toughness.

Qualitative tests are used to verify that the joint is free from defects – they are of sound quality and examples of these are bend tests, macroscopic examination and fracture tests (fillet fracture and nick-break).

2 Test Types, Test Pieces and Test Objectives

Various types of mechanical test are used by material manufacturers/suppliers to verify that plates, pipes, forgings etc, have the minimum property values specified for particular grades.

Design engineers use the minimum property values listed for particular grades of material as the basis for design and the most cost-effective designs are based on an assumption that welded joints have properties that are no worse than those of the base metal.

The quantitative (mechanical) tests carried out for welding procedure qualification are intended to demonstrate that the joint properties satisfy design requirements.

The emphasis in the following sub-sections is on the destructive tests and test methods that are widely used for welded joints.

2.1 Transverse tensile tests

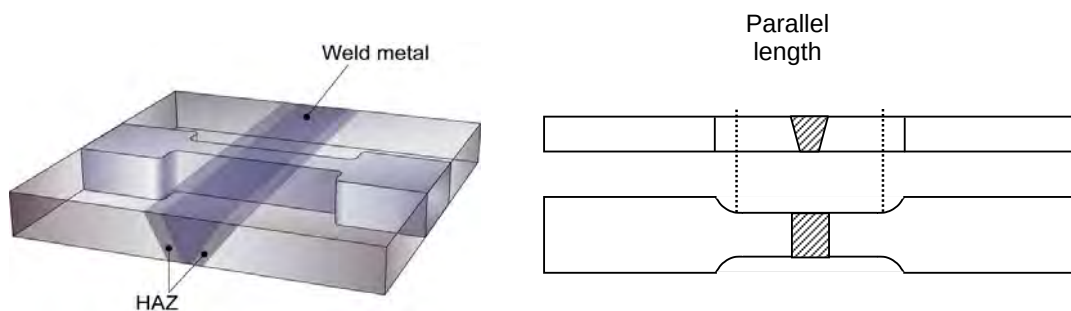
Test objective

Welding procedure qualification tests always require transverse tensile tests to show that the strength of the joint satisfies the design criterion.

Test specimens

A transverse tensile test piece typical of the type specified by European Welding Standards is shown below.

Standards, such as EN 895, that specify dimensions for transverse tensile test pieces require all excess weld metal to be removed and the surface to be free from scratches.



Test pieces may be machined to represent the full thickness of the joint but for very thick joints it may be necessary to take several transverse tensile test specimens to be able to test the full thickness.

Test method

Test specimens are accurately measured before testing. Specimens are then fitted into the jaws of a tensile testing machine and subjected to a continually increasing tensile force until the specimen fractures.

The tensile strength (R_m) is calculated by dividing the maximum load by the cross-sectional area of the test specimen - measured before testing.

The test is intended to measure the **tensile strength of the joint** and thereby show that the basis for design, the base metal properties, remains the valid criterion.

Acceptance criteria

If the test piece breaks in the weld metal, it is acceptable provided the calculated strength is not less than the minimum tensile strength specified, which is usually the minimum specified for the base metal material grade.

In the ASME IX code, if the test specimen breaks outside the weld or fusion zone at a stress above 95% of the minimum base metal strength the test result is acceptable.

2.2 All-weld tensile tests

Test objective

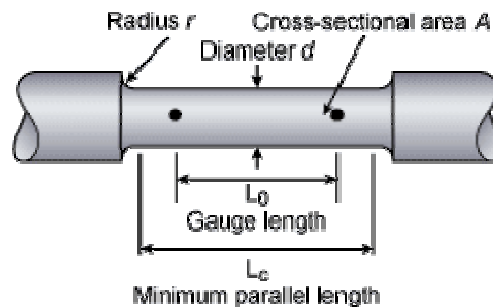
There may be occasions when it is necessary to measure the weld metal strength as part of welding procedure qualification – particularly for elevated temperature designs.

The test is carried out in order to measure tensile strength and also yield (or proof strength) and tensile ductility.

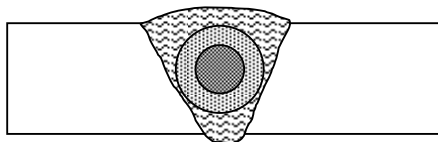
All-weld tensile tests are also regularly carried out by welding consumable manufacturers to verify that electrodes and filler wires satisfy the tensile properties specified by the standard to which the consumables are certified.

Test specimens

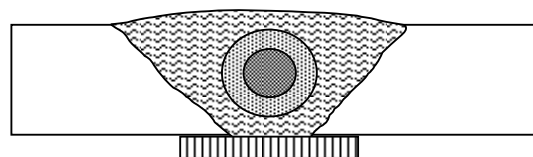
As the name indicates, test specimens are machined from welds parallel with their longitudinal axis and the specimen gauge length must be 100% weld metal.



Round cross section



Round tensile specimen from a welding procedure qualification test piece



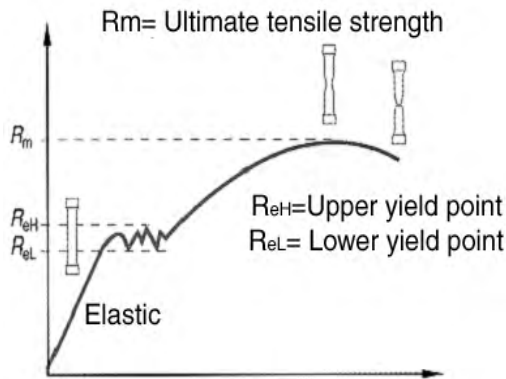
Round tensile specimen from an electrode classification test piece

Test method

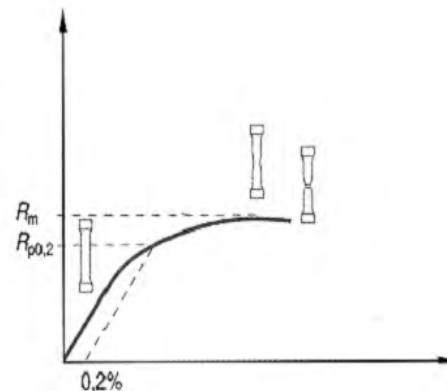
Specimens are subjected to a continually increasing force in the same way that transverse tensile specimens are tested.

Yield (R_e) or proof stress (R_p) are measured by means of an extensometer that is attached to the parallel length of the specimen and is able to accurately measure the extension of the gauge length as the load is increased.

Typical load extension curves and their principal characteristics are shown below.



Load extension curve for a steel that shows a distinct yield point at the elastic limit

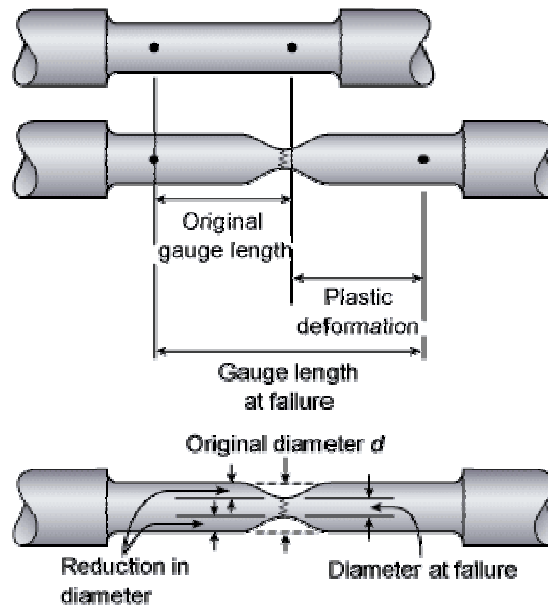


Load-extension curve for a steel (or other metal) that does not show a distinct yield point; proof stress is a measure of the elastic limit

Tensile ductility is measured in two ways:

- Percent elongation of the gauge length
- Percent reduction of area at the point of fracture

The figure below illustrates these two ductility measurements.



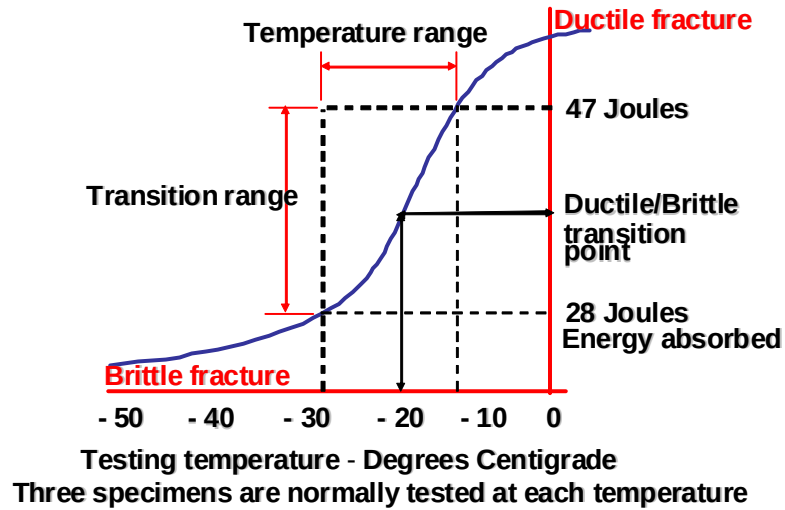
2.3 Impact toughness tests

Test objective

Charpy V notch test pieces have become the internationally accepted method for assessing resistance to brittle fracture by measuring the energy to initiate, and propagate, a crack from a sharp notch in a standard sized specimen subjected to an impact load.

Design engineers need to ensure that the toughness of the steel used for a particular item will be high enough to avoid brittle fracture in service and so impact specimens are tested at a temperature that is related to the design temperature for the fabricated component.

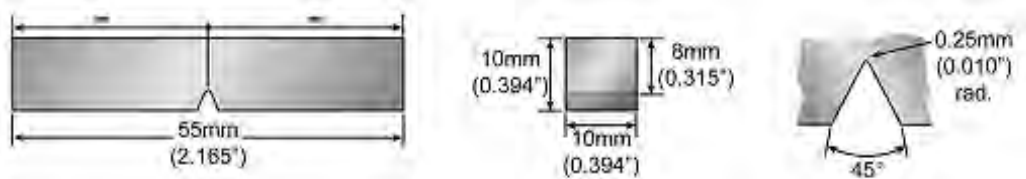
C-Mn and low alloy steels undergo a sharp change in their resistance to brittle fracture as their temperature is lowered so that a steel that may have very good toughness at ambient temperature may show extreme brittleness at sub-zero temperatures – as illustrated in following figure.



The transition temperature is defined as the temperature that is mid-way between the upper shelf (maximum toughness) and lower shelf (completely brittle). In the above the transition temperature is -20°C .

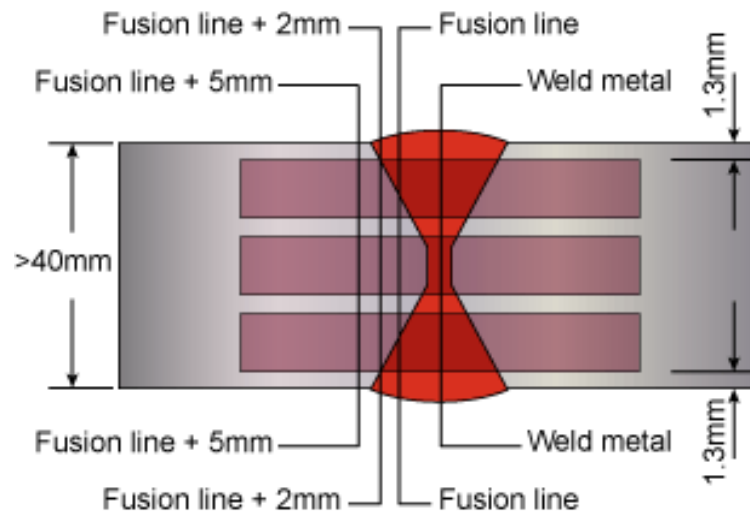
Test specimens

The dimensions for test specimens have been standardised internationally and are shown below for **full sized specimens**. There are also standard dimensions for smaller sized specimens, for example $10 \times 7.5\text{mm}$ and $10 \times 5\text{mm}$.



Charpy V notch test piece dimensions for full sizes specimens

Specimens are machined from welded test plates with the notch position located in different positions according to the testing requirements but typically in the centre of the weld metal and at positions across the HAZ – as shown below.



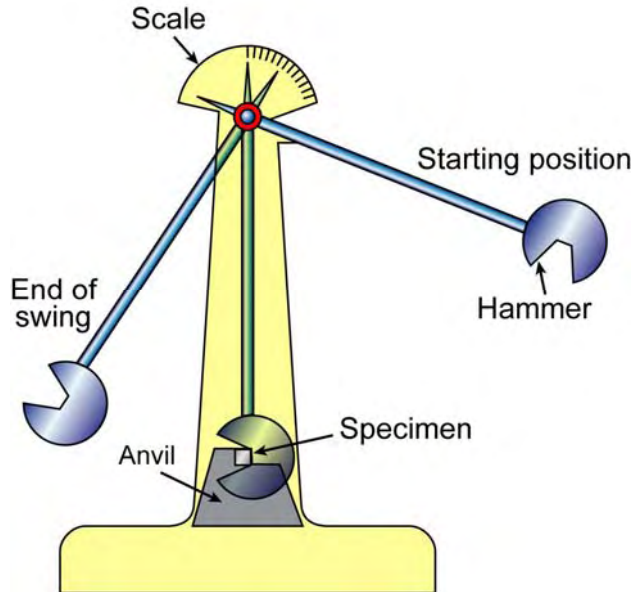
Typical notch positions for Charpy V notch test specimens from double V butt welds

Test method

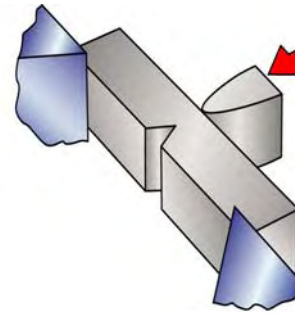
Test specimens are cooled to the specified test temperature by immersion in an insulated bath containing a liquid that is held at the test temperature.

After allowing the specimen temperature to stabilise for a few minutes it is quickly transferred to the anvil of the test machine and a pendulum hammer quickly released so that the specimen experiences an impact load behind the notch.

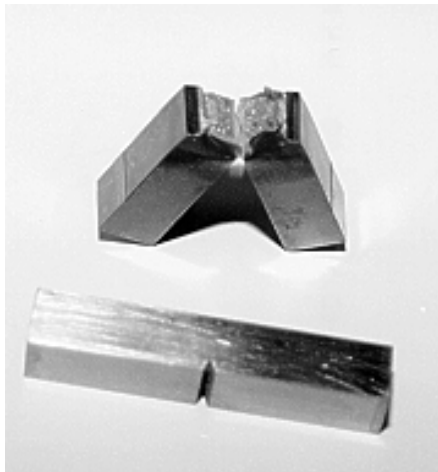
The main features of an impact test machine are shown below.



Impact testing machine



Impact specimen on the anvil showing the hammer position at point of impact.



Charpy V notch test pieces before and after testing

The energy absorbed by the hammer when it strikes each test specimen is shown by the position of the hammer pointer on the scale of the machine. Energy values are given in Joules (or ft-lbs in US specifications).

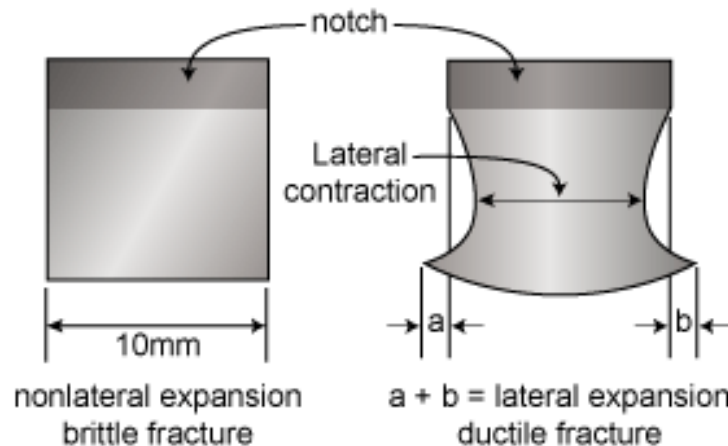
Impact test specimens are taken in triplicate (three specimens for each notch position) as there is always some degree of scatter in the results - particularly for weldments.

Acceptance criteria

Each test result is recorded and an average value calculated for each set of three tests. These values are compared with those specified by the application standard or client to establish whether specified requirements have been met.

After impact testing, examination of the test specimens provides additional information about their toughness characteristics and may be added to the test report:

- Percent crystallinity – the % of the fracture face that has crystalline appearance which indicates brittle fracture; 100% indicates completely brittle fracture
- Lateral expansion – the increase in width of the back of the specimen behind the notch – as indicated below; the larger the value the tougher the specimen



A specimen that exhibits extreme brittleness will show a clean break, both halves of the specimen having a completely flat fracture face with little or no lateral expansion.

A specimen that exhibits very good toughness will show only a small degree of crack extension, without fracture and a high value of lateral expansion.

2.4 Hardness testing

Test objective

The hardness of a metal is its' resistance to plastic deformation. This is determined by measuring the resistance to indentation by a particular type of indenter.

A steel weldment with hardness above a certain maximum may be susceptible to cracking, either during fabrication or in service, and welding procedure qualification testing for certain steels and applications requires the test weld to be hardness surveyed to ensure there are no regions exceed the maximum specified hardness.

Specimens prepared for macroscopic examination can also be used for taking hardness measurements at various positions of the weldment - referred to as a **hardness survey**.

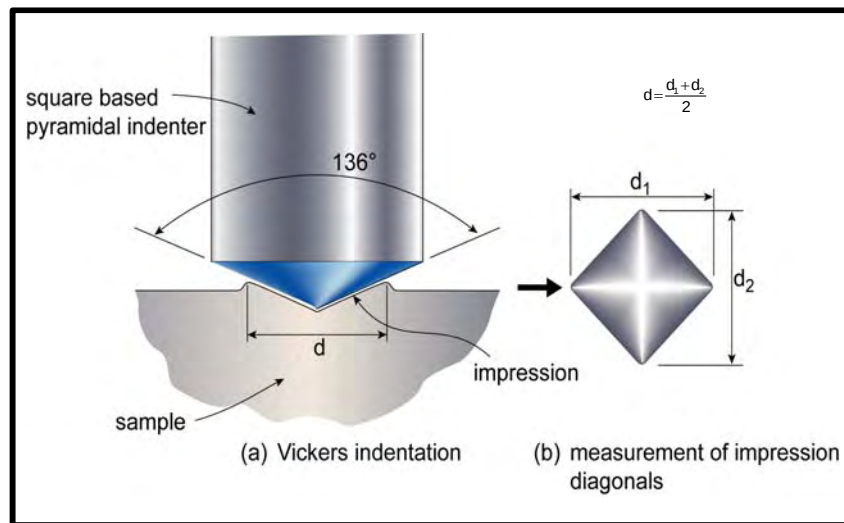
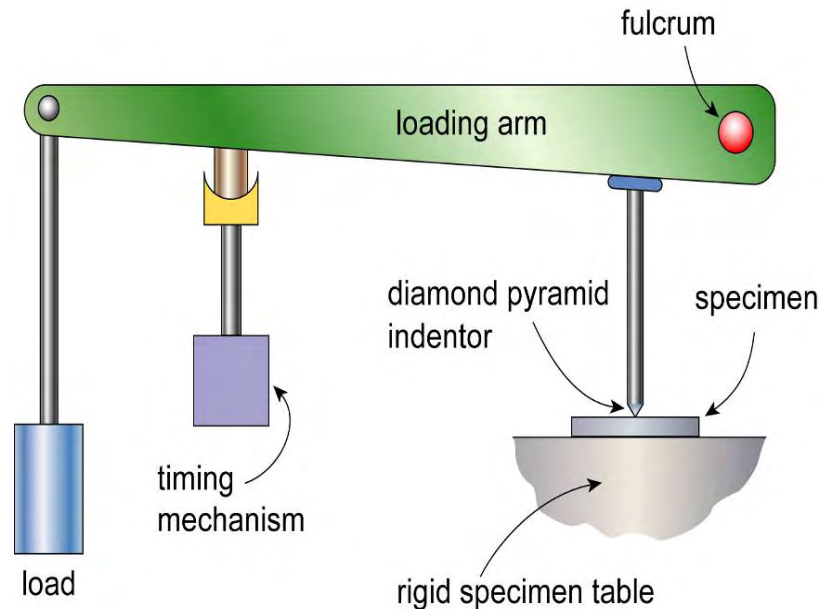
Test methods

There are three widely used methods for hardness testing:

- Vickers hardness test - uses a square-base diamond pyramid indenter.
- Rockwell hardness test - uses a diamond cone indenter or steel ball.
- Brinell hardness test - uses a ball indenter.

The hardness value being given by the size of the indentation produced under a standard load, the smaller the indentation, the harder the metal.

The Vickers method of testing is illustrated below.

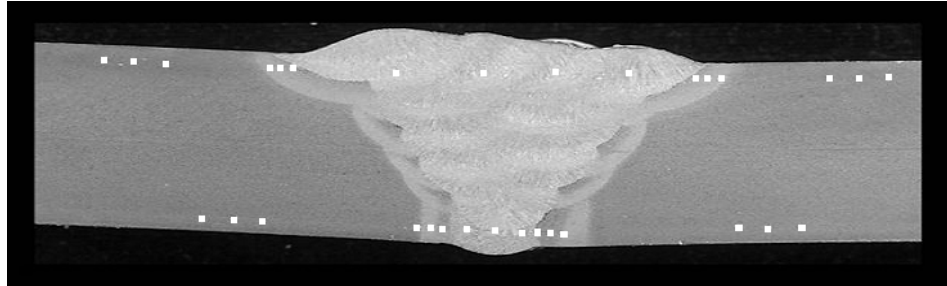


Both the Vickers and Brinell methods are suitable for carrying out hardness surveys on specimens prepared for macroscopic examination of weldments.

A typical hardness survey requires the indenter to measure the hardness in the base metal (on both sides of the weld), the weld metal and across the HAZ (on both sides of the weld).

The Brinell method gives an indentation that is too large to accurately measure the hardness in specific regions of the HAZ and is mainly used to measure hardness of base metals.

A typical hardness survey (using Vickers hardness indenter) is shown below:



Hardness values are shown on test reports as a number followed by letters indicating the test method, for example:

240HV10 = hardness 240, Vickers method, 10kg indenter load

22HRC = hardness 22, Rockwell method, diamond cone indenter (scale C)

238HBW = hardness 238, Brinell method, tungsten ball indenter

2.5 Crack tip opening displacement (CTOD) testing

Test objective

Charpy V notch testing enables engineers **to make judgements** about risks of brittle fracture occurring in steels, but a CTOD test **measures a material property - fracture toughness**.

Fracture toughness data enables engineers to carry out fracture mechanics analyses such as:

- Calculating the size of a crack that would initiate a brittle fracture under certain stress conditions at a particular temperature
- The stress that would cause a certain sized crack to give a brittle fracture at a particular temperature

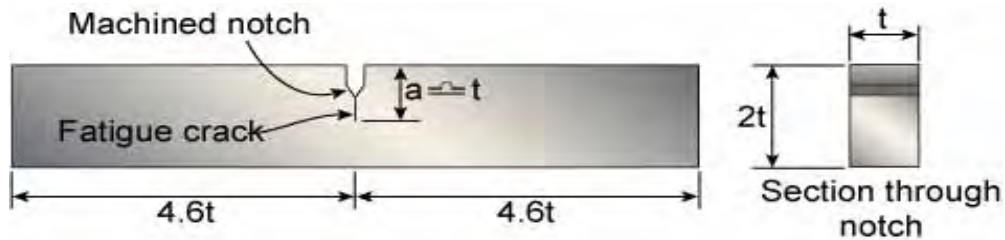
This data is essential for making an appropriate decision when a crack is discovered during inspection of equipment that is in-service.

Test specimens

A CTOD specimen is prepared as a rectangular (or square) shaped bar cut transverse to the axis of the butt weld. A V notch is machined at the centre of the bar, which will be coincident with the test position - weld metal or HAZ.

A shallow saw cut is made at the bottom of the notch and the specimen is then put into a machine that induces a cyclic bending load until a shallow fatigue crack initiates from the saw cut.

The specimens are relatively large – typically having a cross section $B \times 2B$ and length $\sim 10B$ (B = full thickness of the weld). The test piece details are shown below.



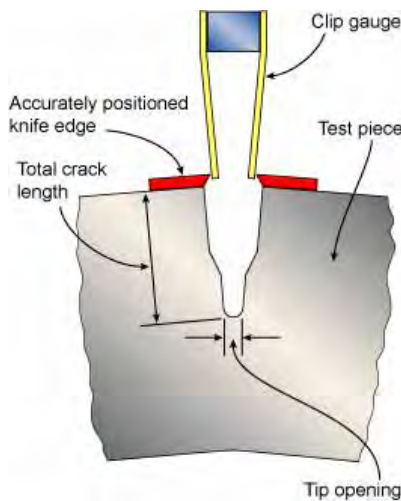
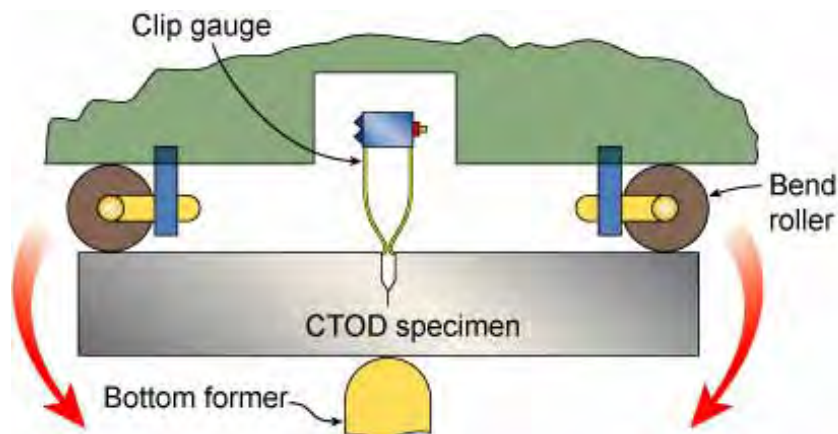
Test method

CTOD specimens are usually tested at a temperature below ambient and the specimen temperature is controlled by immersion in a bath of liquid that has been cooled to the required test temperature.

A load is applied to the specimen to cause bending and induce a concentrated stress at the tip of the crack and a clip gauge, attached to the specimen across the mouth of the machined notch, gives a reading of the increase in width of the crack mouth as the load is gradually increased.

For each test condition (position of notch and test temperature) it is usual practice to carry out three tests.

The figures below illustrate the main features of the CTOD test.



Fracture toughness is expressed as the distance the crack tip opens without initiation of a brittle crack.

The clip gauge enables a chart to be generated showing the increase in width of the crack mouth against applied load from which a CTOD value is calculated.

Acceptance criteria

An application standard or client may specify a minimum CTOD value that indicates ductile tearing. Alternatively, the test may be for information so that a value can be used for an engineering critical assessment.

A very tough steel weldment will allow the mouth of the crack to open widely by ductile tearing at the tip of the crack whereas a very brittle weldment will tend to fracture when the applied load is quite low and without any extension at the tip of the crack.

CTOD values are expressed in millimetres - typical values might be <~0.1mm = brittle behaviour; >~1mm = very tough behaviour.

2.6 Bend testing

Test objective

Bend tests are routinely taken from welding procedure qualification test pieces and sometimes on welder qualification test pieces.

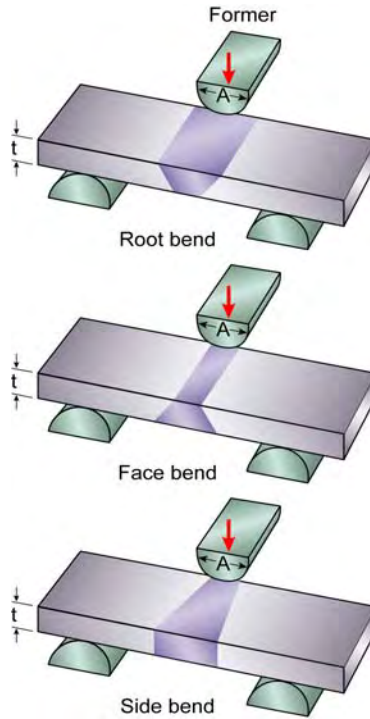
Subjecting specimens to bending is a simple method of verifying there are no significant flaws in the joint. Some degree of ductility is also demonstrated.

Ductility is not actually measured but it is demonstrated to be satisfactory if test specimens can withstand being bent without fracture or fissures above a certain length.

Test specimens

There are four types of bend specimen:

- **Face:** Specimen taken with axis transverse to butt welds up to ~12mm thickness and bent so that the face of the weld is on the outside of the bend (face in tension).
- **Root:** Test specimen taken with axis transverse to butt welds up to ~12mm thickness and bent so that the root of the weld is on the outside of the bend (root in tension).
- **Side:** Test specimen taken as a transverse slice (~10mm) from the full thickness of butt welds >~12mm and bent so that the full joint thickness is tested (side in tension).
- **Longitudinal bend:** Test specimen taken with axis parallel to the longitudinal axis of a butt weld; specimen thickness is ~12mm and the face or root of weld may be tested in tension.



Test method

Bend tests for welding procedure and welder qualification are usually guided bend tests.

Guided means that the strain imposed on the specimen is uniformly controlled by being bent around a former with a certain diameter.

The diameter of the former used for a particular test is specified in the code, having been determined by the type of material being tested and the ductility that can be expected from it after welding and any post weld heat treatment (PWHT).

The diameter of the former is usually expressed as a multiple of the specimen thickness (t) and for C-Mn steel it is typically $4t$ but for materials that have lower tensile ductility the radius of the former may be greater than $10t$.

The standard that specifies the test method will specify the minimum bend angle that the specimen must experience and this is typically $120-180^\circ$.

Acceptance criteria

Bend test pieces should exhibit satisfactory soundness by not showing cracks or any signs of significant fissures or cavities on the outside of the bend.

Small indications less than about 3mm in length may be allowed by some standards.

2.7 Fracture tests

2.7.1 Fillet weld fractures

Test objective

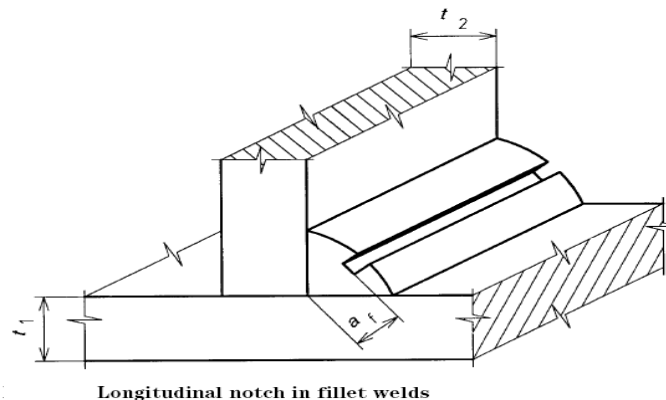
The quality/soundness of a fillet weld can be assessed by fracturing test pieces and examining the fracture surfaces.

This method for assessing the quality of fillet welds may be specified by application standards as an alternative to macroscopic examination.

It is a test method that can be used for welder qualification testing according to European Standards but is not used for welding procedure qualification.

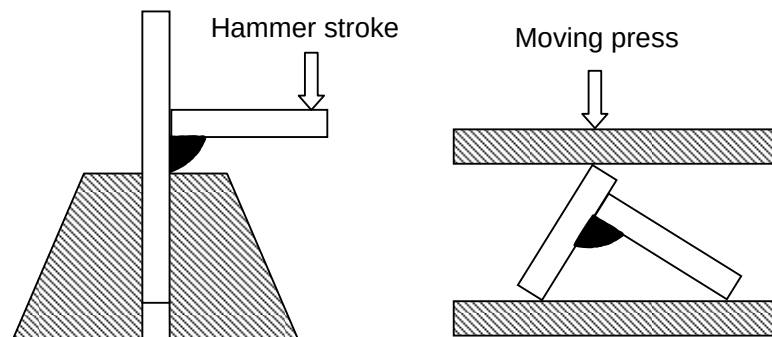
Test specimens

A test weld is cut into short lengths (typically $\geq 50\text{mm}$) and a longitudinal notch is machined into the specimen as shown below. The notch profile may be square, V or U shape.



Test method

Specimens are made to fracture through their throat by dynamic strokes (hammering) or by pressing, as shown below. The welding standard or application standard will specify the number of tests (typically four).



Acceptance criteria

The standard for welder qualification, or application standard, will specify the acceptance criteria for imperfections such as lack of penetration into the root of the joint and solid inclusions and porosity that are visible on the fracture surfaces.

Test reports should also give a description of the appearance of the fracture and location of any imperfection

2.7.2 Butt weld fractures (nick-break tests)

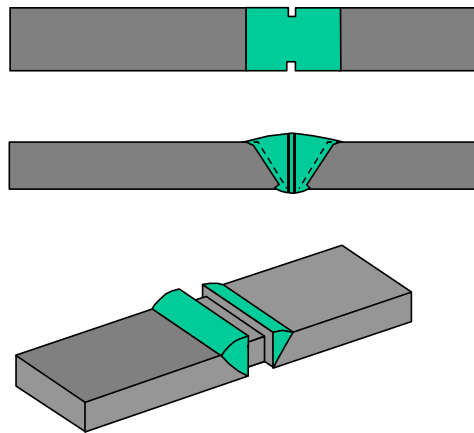
Test objective

The objective of these fracture tests is the same as for fillet fracture tests.

These tests are specified for welder qualification testing to European Standards as an alternative to radiography. They are not used for welding procedure qualification testing.

Test specimens

Test specimens are taken from a butt weld and notched so that the fracture path will be in the central region of the weld. Typical test piece types are shown below.



Test method

Test pieces are made to fracture by hammering or three-point bending.

Acceptance criteria

The standard for welder qualification, or application standard, will specify the acceptance criteria for imperfections such as lack of fusion, solid inclusions and porosity that are visible on the fracture surfaces.

Test reports should also give a description of the appearance of the fracture and location of any imperfection.

3 Macroscopic Examination

Transverse sections from butt and fillet welds are required by the European Standards for welding procedure qualification testing and may be required for some welder qualification testing for assessing the quality of the welds.

This is considered in detail in a separate section of these course notes.

3.1 European Standards for destructive test methods

The following Standards are specified by the European Welding Standards for destructive testing of welding procedure qualification test welds and for some welder qualification test welds.

EN 875	Destructive tests on welds in metallic materials – impact tests – test specimen location, notch orientation and examination.
EN 895	Destructive tests on welds in metallic materials – transverse tensile test.
EN 910	Destructive tests on welds in metallic materials – bend tests.
EN 1321	Destructive tests on welds in metallic materials – macroscopic and microscopic examination of welds.
BS EN 10002	Metallic materials - Tensile testing. Part 1: Method of test at ambient temperature.
BS EN 10002	Tensile testing of metallic materials. Part 5: Method of test at elevated temperatures.

Introduction

Radiographic, ultrasonic, dye penetrant and magnetic particle methods are briefly described below. The relative advantages and limitations of the methods are discussed in terms of their applicability to the examination of welds.

1 Radiographic Methods

In all cases radiographic methods as applied to welds involve passing a beam of penetrating radiation through the test object. The transmitted radiation is collected by some form of sensor, which is capable of measuring the relative intensities of penetrating radiations impinging upon it. In most cases this sensor will be radiographic film, however the use of various electronic devices is on the increase. These devices facilitate so-called real-time radiography and examples may be seen in the security check area at airports. Digital technology has enabled the storing of radiographs using computers. The present discussion is confined to film radiography since this is still by far the most common method applied to welds.

1.1 Sources of penetrating radiation

Penetrating radiation may be generated from high-energy electron beams, in which case they are termed X-rays, or from nuclear disintegrations (atomic fission), in which case they are termed gamma rays. Other forms of penetrating radiation exist but they are of limited interest in weld radiography.

1.2 X-rays

X-rays used in the industrial radiography of welds generally have photon energies in the range 30keV up to 20MeV. Up to 400keV they are generated by conventional X-ray tubes which, dependant upon output, may be suitable for portable or fixed installations. Portability falls off rapidly with increasing kilovoltage and radiation output. Above 400keV X-rays are produced using devices such as betatrons and linear accelerators, not generally suitable for use outside of fixed installations. All sources of X-rays produce a continuous spectrum of radiation, reflecting the spread of kinetic energies of electrons within the electron beam. Low energy radiations are more easily absorbed and the presence of low energy radiations, within the X-ray beam, gives rise to better radiographic contrast and therefore better radiographic sensitivity than is the case with gamma-rays which are discussed below. Conventional X-ray units are capable of performing high quality radiography on steel of up to 60mm thickness, betatrons and linear accelerators in excess of 300mm.

1.3 Gamma rays

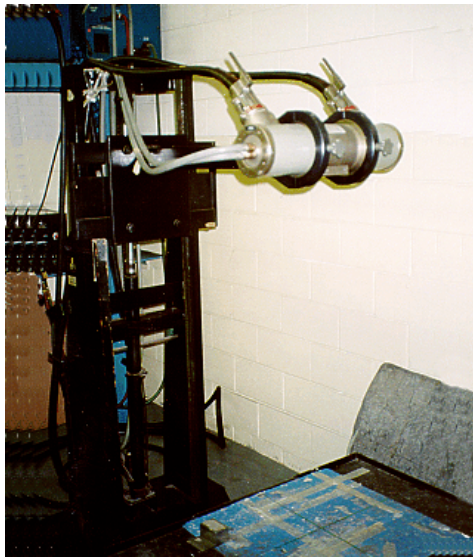
The early sources of gamma rays used in industrial radiography were in general composed of naturally occurring radium. The activity of these sources was not very high, therefore they were physically rather large by modern standards even for quite modest outputs of radiation and the radiographs produced by them were not of a particularly high standard. Radium sources were also extremely hazardous to the user due to the production of radioactive radon gas as a product of the fission reaction. Since the advent of the nuclear age it has been possible to artificially produce isotopes of much higher specific activity than those occurring naturally and which do not produce hazardous fission products. Unlike the X-ray sources gamma sources do not produce a continuous distribution of quantum energies. Gamma sources produce a number of specific quantum energies which are unique for any particular isotope. Four isotopes are in common use for the radiography of welds, they are in ascending order of radiation energy: Thulium 90, Ytterbium 169, Iridium 192 and Cobalt 60. In terms of steel Thulium 90 is useful up to a thickness of 7mm or so, it's energy is similar to that of 90keV X-rays and due to it's high specific activity useful sources can be produced with physical dimensions of less than 0.5mm. Ytterbium 169 has only fairly recently become available as an isotope for industrial use, it's energy is similar to that of 120keV X-rays and it is useful for the radiography of steel up to approximately 12mm thickness. Iridium 192 is probably the most commonly encountered isotopic source of radiation used in the radiographic examination of welds, it has a relatively high specific activity and high output sources with physical dimensions of 2-3mm are in common usage, it's energy is approximately equivalent to that of 500keV X-rays and it is useful for the radiography of steel in the thickness range 10-75mm. Cobalt 60 has an energy approximating to that of 1.2MeV X-rays, due to this relatively high energy, suitable source containers are large and rather heavy. Cobalt 60 sources are for this reason not fully portable. They are useful for the radiography of steel in the thickness range 40-150mm. The major advantages of using isotopic sources over X-rays are:

- a) Increased portability;
- b) No need for a power source;
- c) Lower initial equipment costs.

Against this the quality of radiographs produced by gamma ray techniques is inferior to that produced by X-ray techniques, the hazards to personnel may be increased (if the equipment is not properly maintained, or if the operating personnel have insufficient training), and due to their limited useful lifespan new isotopes have to be purchased on a regular basis (so that the operating costs of an gamma ray source may exceed those of an X-ray source).

1.4 Radiography of welds

Radiographic techniques depend upon detecting differences in absorption of the beam ie, changes in the effective thickness of the test object, in order to reveal defective areas. Volumetric weld defects such as slag inclusions (except in some special cases where the slag absorbs radiation to a greater extent than does the weld metal) and various forms of gas porosity are easily detected by radiographic techniques due to the large negative absorption difference between the parent metal and the slag or gas. Planar defects such as cracks or lack of sidewall or interrun fusion are much less likely to be detected by radiography since they may cause little or no change in the penetrated thickness. Where defects of this type are likely to occur other NDE techniques such as ultrasonic testing are preferable to radiography. This lack of sensitivity to planar defects makes radiography an unsuitable technique where a fitness-for-purpose approach is taken when assessing the acceptability of a weld. However, film radiography produces a permanent record of the weld condition, which can be archived for future reference; it also provides an excellent means of assessing the welder's performance and for these reasons it is often still the preferred method for new construction.



X-ray equipment.



Gamma ray equipment.



X-ray of a welded seam showing porosity.

1.5 Radiographic testing

Advantages	Limitations
Permanent record	Health hazard. Safety (Important)
Good for sizing non-planar defects/flaws	Classified workers, medicals required
Can be used on all materials	Sensitive to defect orientation
Direct image of defect/flaws	Not good for planar defect detection
Real-time imaging	Limited ability to detect fine cracks
Can be positioned inside pipe (productivity)	Access to both sides required
Very good thickness penetration	Skilled interpretation required
No power required with gamma	Relatively slow
	High capital outlay and running costs Isotopes have a half life (cost)

2 Ultrasonic Methods

The velocity of ultrasound in any given material is a constant for that material and ultrasonic beams travel in straight lines in homogeneous materials. When ultrasonic waves pass from a given material with a given sound velocity to a second material with different velocity refraction, and a reflection of the sound beam will occur at the boundary between the two materials. The same laws of physics apply equally to ultrasonic waves as they do to light waves. Ultrasonic waves are refracted at a boundary between two materials having different acoustic properties, so probes may be constructed which can beam sound into a material at (within certain limits) any given angle. Because sound is reflected at a boundary between two materials having different acoustic properties ultrasound is a useful tool for the detection of weld defects. Since velocity is a constant for any given material and sound travels in a straight line (with the right equipment) ultrasound can also be utilised to give accurate positional information about a given reflector. Careful observation of the echo pattern of a given reflector and its behaviour as the ultrasonic probe is moved together with the positional information obtained above and a knowledge of the component history enables the experienced ultrasonic operator to classify the reflector as say slag, lack of fusion or a crack.

2.1 Equipment for ultrasonic testing

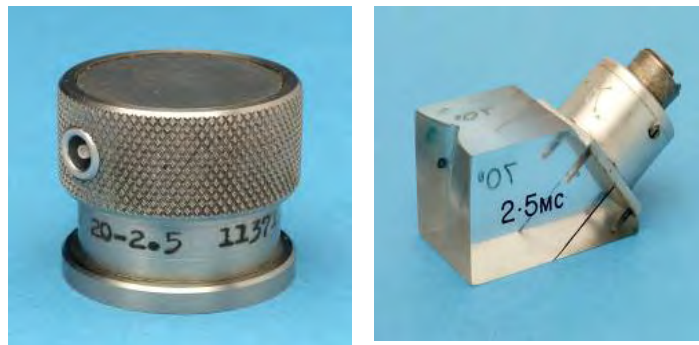
Equipment for manual ultrasonic testing consists of:

- A flaw detector:
 - Pulse generator.
 - Adjustable time base generator with an adjustable delay control.
 - Cathode ray tube with fully rectified display.
 - Calibrated amplifier with a graduated gain control or attenuator.
- An ultrasonic probe:
 - Piezo-electric crystal element capable of converting electrical vibrations into mechanical vibrations and vice-versa.
 - Probe shoe, normally a Perspex block to which the crystal is firmly attached using a suitable adhesive.
 - Electrical and/or mechanical crystal damping facilities to prevent excessive ringing.

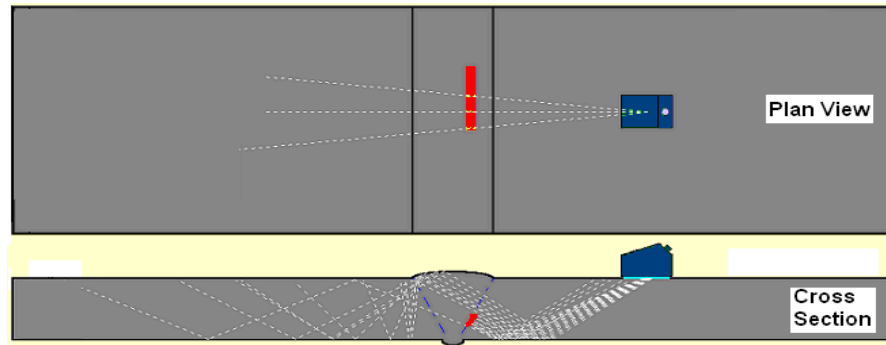
Such equipment is lightweight and extremely portable. Automated or semi-automated systems for ultrasonic testing utilise the same basic equipment although since in general this will be multi-channel equipment it is bulkier and less portable. Probes for automated systems are set in arrays and some form of manipulator is necessary to feed positional information about the probes to the computer. Automated systems generate very large amounts of data and make large demands upon the RAM of the computer. Recent advances in automated UT have led to a reduced amount of data being recorded for a given length of weld. Simplified probe arrays have greatly reduced the complexity of setting-up the automated system to carry out a particular task. Automated UT systems now provide a serious alternative to radiography on such constructions as pipelines where a large number of similar inspections allow the unit cost of system development to be reduced to a competitive level.



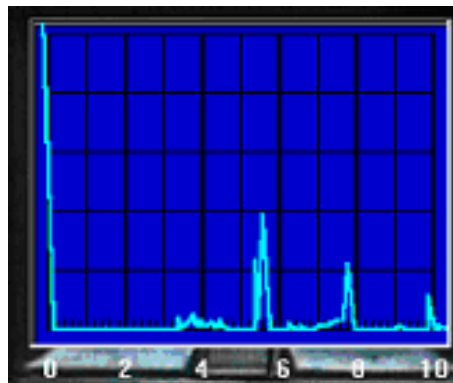
Ultrasonic equipment.



Compression and a shear wave probe.



Example of a scanning technique with a shear wave probe.



Typical screen display when using a shear wave probe.

2.2 Ultrasonic testing

Advantages	Limitations
Portable (no mains power) battery	No permanent record
Direct location of defect (3 dimensional)	Only ferritic materials (mainly)
Good for complex geometry	High level of operator skill required
Safe operation (can be done next to someone)	Calibration of equipment required
Instant results	Special calibration blocks required
High penetrating capability	No good for pin pointing porosity
Can be done from one side only	Critical of surface conditions (clean smooth)
Good for finding planar defects	Will not detect surface defects
	Material thickness >8mm due to dead zone

3 Magnetic Particle Testing

Surface breaking or very near surface discontinuities in ferromagnetic materials give rise to leakage fields when high levels of magnetic flux are applied. These leakage fields will attract magnetic particles (finely divided magnetite) to themselves and this leads to the formation of an indication. The magnetic particles may be visibly or fluorescently pigmented in order to provide contrast with the substrate or conversely the substrate may be lightly coated with a white background lacquer in order to contrast with the particles. Fluorescent magnetic particles provide the greatest sensitivity. The particles will normally be in a liquid suspension, usually applied by spraying. In certain cases dry particles may be applied by a gentle jet of air. The technique is applicable only to ferromagnetic materials, which are at a temperature below the curie point (about 650°C). The leakage field will be greatest for linear discontinuities lying at right angles to the magnetic field. This means that for a comprehensive test the magnetic field must normally be applied in two directions, which are mutually perpendicular. The test is economical to carry out both in terms of equipment costs and rapidity of inspection. The level of operator training required is relatively low.



Magnetic particle inspection using a yoke.



Crack found using magnetic particle inspection.

3.1 Magnetic particle testing

Advantages	Limitations
Inexpensive equipment	Only magnetic materials
Direct location of defect	May need to demagnetise components
Not critical of surface conditions	Access may be a problem for the yoke
Could be applied without power	Need power if using a yoke
Low skill level	No permanent record
Sub-defects surface 1-2mm	Calibration of equipment
Quick, instant results	Testing in two directions required
Hot testing (using dry powder)	Need good lighting - 500 lux minimum
Can be used in the dark (UV light)	

4 Dye Penetrant Testing

Any liquid that has good wetting properties will act as a penetrant. Penetrants are attracted into surface-breaking discontinuities by capillary forces. Penetrant, which has entered a tight discontinuity, will remain even when the excess penetrant is removed. Application of a suitable developer will encourage the penetrant within such discontinuities to bleed out. If there is a suitable contrast between the penetrant and the developer an indication visible to the eye will be formed. This contrast may be provided by either visible or fluorescent dyes. Use of fluorescent dyes considerably increases the sensitivity of the technique. The technique is not applicable at extremes of temperature, as at low temperatures (below 5°C) the penetrant vehicle, normally oil, will become excessively viscous and causing an increase in the penetration time with a consequent decrease in sensitivity. At high temperatures (above 60°C) the penetrant will dry out and the technique will not work.



Methods of applying the red dye during dye penetrant inspection.



Crack found using dye penetrant inspection.

4.1 Dye penetrant

Advantages	Limitations
All materials (non porous)	Will only detect defects open to the surface
Portable	Requires careful space preparation
Applicable to small parts with complex geometry	Not applicable to porous surfaces
Simple	Temperature dependant
Inexpensive	Cannot retest indefinitely
Sensitive	Potentially hazardous chemicals
Relatively low skill level (easy to interpret)	No permanent record
Relatively low <u>skill</u> level (easy to interpret)	Time lapse between application and results
	Messy

5 Surface Crack Detection (Magnetic Particle/Dye Penetrant): General

When considering the relative value of NDE techniques it should not be forgotten that most catastrophic failures initiate from the surface of a component, therefore the value of the magnetic particle and dye penetrant techniques should not be under-estimated. Ultrasonic inspection may not detect near-surface defects easily since the indications may be masked by echoes arising from the component geometry and should therefore be supplemented by an appropriate surface crack detection technique for maximum test confidence.

General

When structures and pressurised items are fabricated by welding, it is essential that all the welded joints are sound and have suitable properties for their application.

Control of welding is achieved by means of Welding Procedure Specifications (WPSs) that give detailed written instructions about the welding conditions that must be used to ensure that welded joints have the required properties.

Although WPSs are shop floor documents to instruct welders, welding inspectors need to be familiar with them because they will need to refer to WPSs when they are checking that welders are working in accordance with the specified requirements.

Welders need to be able to understand WPSs, have the skill to make welds that are not defective and demonstrate these abilities before being allowed to make production welds.

1 Qualified Welding Procedure Specifications

It is industry practice to use **qualified WPSs** for most applications.

A welding procedure is **usually qualified** by making a test weld to demonstrate that the properties of the joint satisfy the requirements specified by the application standard and the client/end user.

Demonstrating the mechanical properties of the joint is the principal purpose of qualification tests, but showing that a defect-free weld can be produced is also very important.

Production welds made in accordance with welding conditions similar to those used for a test weld should have similar properties and therefore be fit for their intended purpose.

Figure 1 is an example of a typical WPS written in accordance with the European Welding Standard format giving details of all the welding conditions that need to be specified.

1.1 Welding standards for procedure qualification

European and American Standards have been developed to give comprehensive details about:

- How a welded test piece must be made to demonstrate joint properties.
- How the test piece must be tested.
- What welding details need to be included in a WPS.
- The range of production welding allowed by a particular qualification test weld.

The principal **European Standards** that specify these requirements are:

EN ISO 15614 Specification and qualification of welding procedures for metallic materials – Welding procedure test

Part 1: Arc and gas welding of steels and arc welding of nickel and nickel alloys

Part 2: Arc welding of aluminium and its alloys

The principal **American Standards** for procedure qualification are:

ASME Section IX Pressurised systems (vessels and pipework)

AWS D1.1 Structural welding of steels

AWS D1.2 Structural welding of aluminium

1.2 The qualification process for welding procedures

Although qualified WPSs are usually based on test welds that have been made to demonstrate weld joint properties; welding standards also allow qualified WPSs to be written based on other data (for some applications).

Some alternative ways that can be used for writing qualified WPSs for some applications are:

- **Qualification by adoption of a standard welding procedure** – test welds previously qualified and documented by other manufacturers.
- **Qualification based on previous welding experience** – weld joints that have been repeatedly made and proved to have suitable properties by their service record.

Procedure qualification to European Standards by means of a test weld (and similar in ASME Section IX and AWS) requires a sequence of actions that is typified by those shown by **Table 1**.

A successful procedure qualification test is completed by the production of a Welding Procedure Qualification Record (WPQR), an example of which is shown by **Figure 2**.

1.3 Relationship between a WPQR and a WPS

Once a WPQR has been produced, the welding engineer is able to write **qualified WPSs** for the various production weld joints that need to be made.

The welding conditions that are allowed to be written on a qualified WPS are referred to as the **qualification range** and this range depends on the welding conditions used for the test piece (the as-run details) and form part of the WPQR.

Welding conditions are referred to as **welding variables** by European and American Welding Standards and are classified as either **essential** or **non-essential variables**.

These variables can be defined as follows:

- **Essential variable:** A variable that has an effect on the mechanical properties of the weldment (and if changed beyond the limits specified by the standard will require the WPS to be re-qualified).
- **Non-essential variable:** A variable that must be specified on a WPS but does not have a significant effect on the mechanical properties of the weldment (and can be changed **without need for re-qualification** but will require a new WPS to be written).

It is because essential variables can have a significant effect on mechanical properties that they are the controlling variables that govern the qualification range and determine what can be written in a WPS.

If a welder makes a production weld using conditions outside the qualification range given on a particular WPS, there is danger that the welded joint will not have the required properties and there are then two options:

- 1 Make another test weld using similar welding conditions to those used for the affected weld and subject this to the same tests used for the relevant WPQR to demonstrate that the properties still satisfy specified requirements.
- 2 Remove the affected weld and re-weld the joint strictly in accordance with the designated WPS.

Most of the welding variables that are classed as essential are the same in both the European and American Welding Standards but their qualification ranges may differ.

Some application standards specify their own essential variables and it is necessary to ensure these are taken into consideration when procedures are qualified and WPSs written.

Examples of essential variables (according to European Welding Standards) are given in Table 2.

2 Welder Qualification

The use of qualified WPSs is the accepted method for controlling production welding but this will only be successful if the welders are able to understand and work in accordance with them.

Welders also need to have the skill to consistently produce sound welds (free from defects).

Welding Standards have been developed to give guidance on what particular test welds are required in order to show that welders have the required skills to make particular types of production welds in particular materials.

2.1 Welding standards for welder qualification

The principal **European Standards** that specify requirements are:

EN 287-1	Qualification test of welders – Fusion welding Part 1: Steels
EN ISO 9606-2	Qualification test of welders – Fusion welding Part 2: Aluminium and aluminium alloys
EN 1418	Welding personnel – Approval testing of welding operators for fusion welding and resistance weld setters for fully mechanised and automatic welding of metallic materials

The principal **American Standards** that specify requirements for welder qualification are:

ASME Section IX Pressurised systems (vessels & pipework)

AWS D1.1	Structural welding of steels
AWS D1.2	Structural welding of aluminium

2.2 The qualification process for welders

Qualification testing of welders to European Standards requires test welds to be made and subjected to specified tests to demonstrate that the welder is able to understand the WPS and to produce a sound weld.

For manual and semi-automatic welding the emphasis of the tests is to demonstrate the ability to manipulate the electrode or welding torch.

For mechanised and automatic welding the emphasis is on demonstrating that welding operators have the ability to control particular types of welding equipment.

American Standards allow welders to demonstrate that they can produce sound welds by subjecting their first production weld to NDT.

Table 3 shows the steps required for qualifying welders in accordance with European Standards.

Figure 3 shows a typical Welder Qualification Certificate in accordance with European Standards.

2.3 Welder qualification and production welding allowed

The welder is allowed to make production welds within the range of qualification recorded on his Welder Qualification Certificate.

The range of qualification is based on the limits specified by the Welding Standard for **welder qualification essential variables** – defined as:

A variable that if changed beyond the limits specified by the Welding Standard may require greater skill than has been demonstrated by the test weld.

Some welding variables that are classed as essential for welder qualification are the **same types** as those classified as essential for welding procedure qualification, but the range of qualification may be significantly wider.

Some essential variables are specific to welder qualification.

Examples of welder qualification essential variables are given in Table 4.

2.4 Period of validity for a welder qualification certificate

A welder's qualification begins from the date of welding of the test piece.

The European Standard allows a qualification certificate to remain valid for a period of two years, provided that:

- The welding co-ordinator, or other responsible person, can confirm that **the welder has been working within the initial range of qualification.**
- Working within the initial qualification range is confirmed every six months.

2.5 Prolongation of welder qualification

A welder's qualification certificate can be prolonged every two years by an examiner/examining body but before prolongation is allowed certain conditions need to be satisfied:

- Records/evidence are available that can be traced to the welder and the WPSs used for production welding.
- Supporting evidence must relate to volumetric examination of the welder's production welds (RT or UT) on two welds made during the six months prior to the prolongation date.
- Supporting evidence welds must satisfy the acceptance levels for imperfections specified by the European welding standard and have been made under the same conditions as the original test weld.

Table 1 Typical sequence for welding procedure qualification by means of a test weld

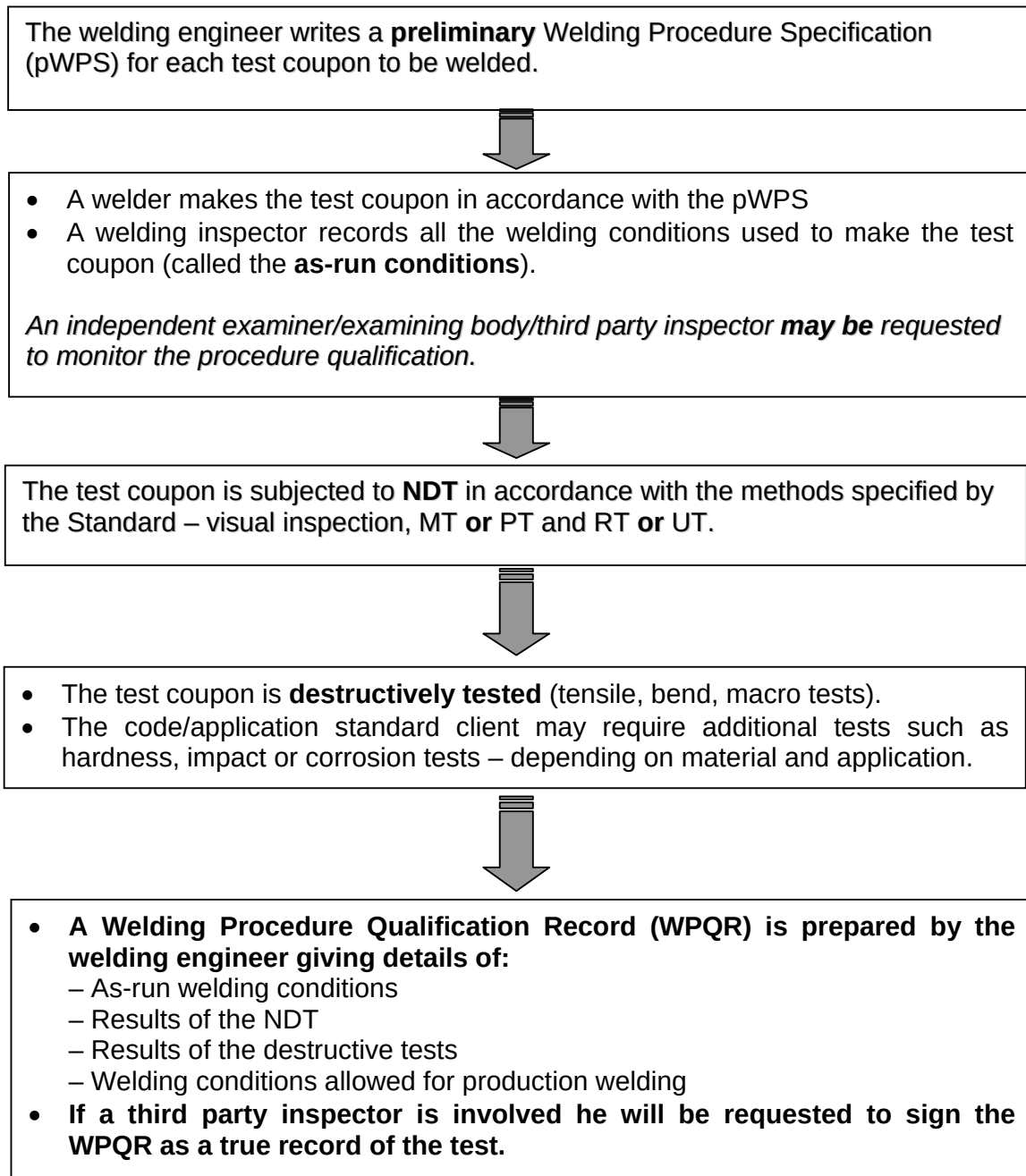


Table 2 Typical examples of WPS essential variables according to European Welding Standards

Variable	Range for procedure qualification
Welding process	No range – process qualified must be used in production.
PWHT	Joints tested after PWHT and only qualify PWHT production joints. Joints tested as-welded only qualify as-welded production joints.
Parent material type	Parent materials of similar composition and mechanical properties are allocated the same Material Group No; qualification only allows production welding of materials with the same Group No.
Welding consumables	Consumables for production welding must have the same European designation – as a general rule.
Material thickness	A thickness range is allowed – below and above the test coupon thickness.
Type of current	AC only qualifies for AC; DC polarity (+ve or -ve) cannot be changed; pulsed current only qualifies for pulsed current production welding.
Preheat temperature	The preheat temperature used for the test is the minimum that must be applied.
Interpass temperature	The highest interpass temperature reached in the test is the maximum allowed.
Heat input (HI)	When impact requirements apply maximum HI allowed is 25% above test HI. When hardness requirements apply minimum HI allowed is 25% below test HI.

Table 3 The stages for qualification of a welder

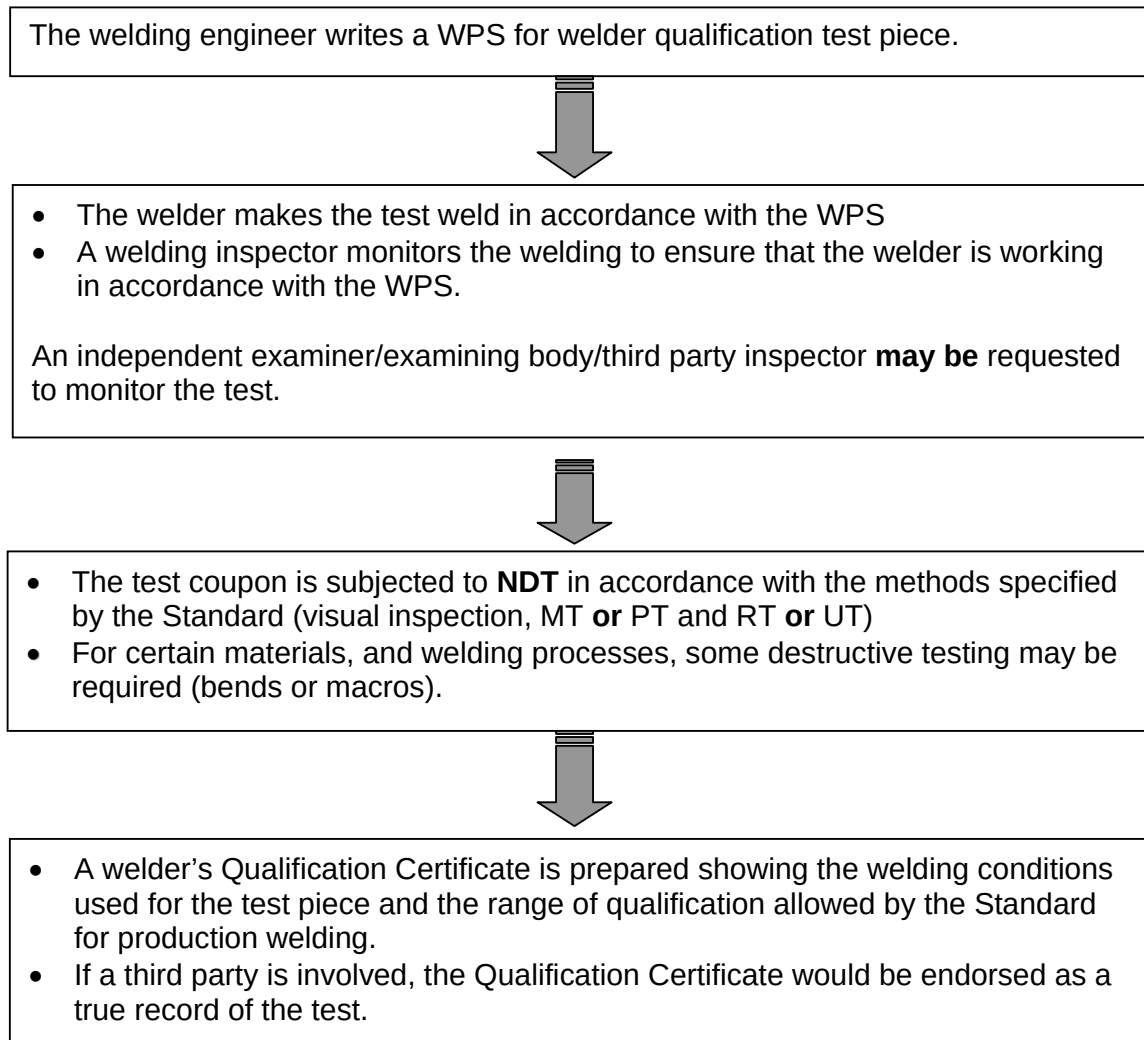


Table 4 Typical examples of welder qualification essential variables according to European Welding Standards

Variable	Range for welder qualification
Welding process	No range – process qualified is process that a welder can use in production.
Type of weld	Butt welds cover any type of joint except branch welds. Fillet welds only qualify fillets.
Parent material type	Parent materials of similar composition and mechanical properties are allocated the same Material Group No; qualification only allows production welding of materials with the same Group No. but the Groups allow much wider composition ranges than the procedure Groups.
Filler material	Electrodes and filler wires for production welding must be of the same form as the test (solid wire, flux-cored etc); for MMA coating type is essential.
Material thickness	A thickness range is allowed; for test pieces above 12mm allow $\geq 5\text{mm}$.
Pipe diameter	Essential and very restricted for small diameters: Test pieces above 25mm allow $\geq 0.5 \times \text{diameter}$ used (minimum 25mm).
Welding positions	Position of welding very important; H-L045 allows all positions (except PG).

Weldspec

WPS record number	WPS - 031	Revision	0	Qualified to	EN 15614-1: 2004
Date	12/04/2006	Company name	TWI Ltd		
Supporting PQR(s)	PQR-031 - Rev 0				
Reference docs.					

MATERIAL/JOINTS QUALIFIED			WELD/TEST CONDITIONS		
Joint type	Butt plate ss mb nb, bs gg ng : T-Butt ss bs : Fillet plate : Butt pipe ss mb nb : Fillet pipe			Without PWHT	
Parent metal(s)	Groups 8-8				
Notes					

TEST PIECE MATERIAL SPECIFICATION			MATERIAL SIZE QUALIFIED		
Type	ASTM A213 TP316L	Grp-no.	8.1	Material thickness fillet (mm)	3.0 7.2
Welded to	ASTM A213 TP316L	Grp-no.	8.1	Material thickness butt (mm)	3.0 12.0
Backing	ASTM A213 TP316L	Grp-no.	8.1	Outside diameter (mm)	57.2 no max.
				Throat thickness (mm)	No Min No Max

WELDING PROCESSES	
Welding process	TIG
Type	Manual

FILLER METALS	
Filler metal manufacturer, trade name	METRODE 316S92
Filler metal designation type	Chemical
Filler metal designation	EN 12072 19 12 3 L
Filler metal size (mm)	2.4
Deposited thickness (mm)	3.0 - 12.0

POSITION	
Position of groove	All positions

PREHEAT	
Preheat temperature (°C)	4
Maximum interpass temperature (°C)	150

GAS	
Shielding gas type	EN 439 - I1
Flow rate (l/min)	10 to 12
Manufacturer, Trade name	n/a
Backing gas: Type	EN 439 - I1
Flow rate (l/min)	4
Manufacturer, Trade name	n/a

ELECTRICAL	
Filler metal size (mm)	2.4
Amperes	80 to 140
Volts	10 to 12
Travel speed (mm/min)	30 to 60
Maximum heat input (kJ/mm)	2.0
Tungsten size (mm)	2.4
Tungsten type	WT 20 (2% Thoria)
Current/polarity	DC -VE
DC pulsing current	None

TECHNIQUE	
String or weave	Stringer
Maximum width of run (mm)	n/a
Orifice/gas cup size	12
Multi/Single pass per side	Multi-pass only
Closed or out-of-chamber	Not applicable
Surface preparation	degreased before welding
Initial/interpass cleaning	Brushing
Back gouging method	None

Figure 1 Example of a Welding Procedure Specification (WPS) to EN 15614 format.

Weldspec

PQR record number	WIS 5-002	Revision 0	pWPS record number	WIS 5 - p002	Revision 0
Date	27/03/2006				

Examiner/examining body	Third Party Ltd	Manufacturer	TWI Ltd
Reference number	TPL/TWI/WIS-002	Address	
Code/Testing standard	EN 15614-1: 2004		

EXTENT OF APPROVAL (JOINT/WELDING CONDITIONS)

Joint type	Butt plate ss mb nb, bs gg ng : T-Butt ss bs : Fillet plate : Fillet pipe
Parent metal(s)	Groups 1-1
Coupon thickness (mm)	17.5 - 70.0
Coupon outside diameter (mm)	Greater than 500.0
Fillet throat thickness (mm)	No Restriction
Branch angle (deg.)	n/a
Preheat (°C)	50
Interpass temperature (°C)	200
PWHT and/or ageing	-

EXTENT OF APPROVAL (PROCESS)

Welding process	111: MMA
Welding process type	Manual
Welded thickness (mm)	17.5 - 70.0
Welded outside diameter (mm)	Greater than 500.0
Filler metal type	en 499 e 46 6 mn 1 ni b 12 h 5
Shielding gas/flux	none
Welding positions	PA,PC,PE,PF
Preheat temperature (°C)	50
Interpass temperature (°C)	200
Current/polarity	DC +VE
Multi/Single pass per side	Multi-pass only
Heat input (kJ/mm)	Max 3.2
Metal transfer mode	n/a
Backing gas	n/a

Figure 2.1 Example of WPQR (Qualification Range) to EN 15614 format.

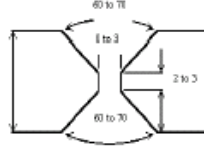
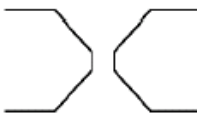
Weldspec

PQR record number	WIS 5-002	Revision 0	pWPS record number	WIS 5 - p002	Revision 0
Date	27/03/2006				

TEST PIECE MATERIAL SPECIFICATION

	Product form	Specification (type or grade)	Grp-no.	Size	Sch.	Thick. (mm)	Dia.(mm)
Welded to:	Plate	BS 10025	1.1	-	-	35	-
and tested:	Plate	BS 10025	1.1	-	-	35	-
Notes	Without PWHT. With Impacts						

TEST PIECE JOINT SPECIFICATION

Joint design	Butt-plate bs gg		
Backing:	gg: gouging or grinding		
Retainers			
Groove angle (deg.)	60		
Root opening (mm)	2.5		
Root face (mm)	2		

WELDING PROCESSES

Welding process	111: MMA
Type	Manual

FILLER METALS

Filler metal manufacturer, trade name	ESAB OK 53.08 Hytuf 1Ni
Filler metal designation type	Yield strength
Filler metal designation	EN 499 E 46 6 Mn1Ni B12 H5
Filler metal size (mm)	3.25 & 4.0
Deposited thickness (mm)	35
MMA Electrode coating	B basic

POSITION

Position of groove	PF
--------------------	----

PREHEAT

Preheat temperature (°C)	50
Maximum interpass temperature (°C)	200

ELECTRICAL

Filler metal size (mm)	3.25 & 4.0
Amperes	3.25mm = 110; 4.0mm = 130
Volts	23 to 25
Electrode run out length (mm)	3.25mm=75min.; 4.0mm=125min.
Travel speed (mm/min)	60 to 70
Maximum heat input (kJ/mm)	2.6
Current/polarity	DC +ve

TECHNIQUE

String or weave	Stringer and Weave
Maximum width of run (mm)	8
Multi/Single pass per side	Multi-pass
Surface preparation	ground
Initial/interpass cleaning	Brushing and Grinding
Back gouging method	arc-air

Figure 2.2 Example of a WPQR document (test weld details) to EN 15614 format.

Weldspec

PQR record number	WIS 5-002	Revision 0	pWPS record number	WIS 5 - p002	Revision 0
Date	27/03/2006				

TENSILE TESTS

Type/Number	Re (N/mm ²)	Rm (N/mm ²)	A% on	Z%	Fracture location	Remarks
transverse	480	610	32	35	Ductile-Base Metal	
transverse	473	598	33	35	Ductile-Base Metal	

Comments: 2 Transverse tensile tests according to EN 895

GUIDED BEND TESTS

Type/Number	Bend angle	Elongation*	Results
4 Side bend tests as per 7.4.3 and EN 910	EN 25817		Acceptable

Comments:

TOUGHNESS TESTS

Notch location/direction	Temperature (°C)	Values			Average (J)	Remarks
		(J)	(J)	(J)		
weld metal (surface)	-46	157	146	149	150.67	
weld metal (root)	-46	127	136	132	131.67	
FL (surface)	-46	67	78	63	69.33	
FL + 2 (surface)	-46	105	113	143	120.33	
FL + 5 (surface)	-46	216	203	215	211.33	

Comments:

CERTIFICATION

Welder's name	ID Number	Stamp number	Mechanical testing by	The Test House
R.A.T. Catcher			Laboratory test number	TTH - 1341-2006
			Test file number	1341-2006
			Tests conducted by	I. A. M. Tougher

Certified that test welds were performed, welded and tested satisfactorily in accordance with the requirements of the code/testing standard indicated above.

Examiner or examining body

Manufacturer

Name	Signature	Name	Signature
Date		Date	

Signature 3 **Signature 4**

Name	Signature	Name	Signature
Date		Date	

Weldspec 4.5.002
Catalog n° PQR00012

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Figure 2.3 Example of WPQR document (details of weld test) to EN 15614 format.



Welderqual

EN DESIGNATION

Designation	EN287-1, 111, T, BW, 1.1, B, H4.27, D163.28, H-L045, ss, no
-------------	---

Welder's name	A. Weaver	Test date	06/07/2006
ID Number	AW-3463	WPQ record number	3463-001
Date of birth	12.3.79	Standard test number	n/a
Stamp number	3463	WPS record number	WPS - 013
Company name	XYZ Fabrications	Qualification code	EN 287-1: 2004
Division	North East	Examining body	Third Party Ltd
Job knowledge	Not tested	Reference no.	TP/XYZ/3463-1
		Expiry date	05/07/2007

BASE METALS

	Product form	Specification (type or grade)	Grp.no.	Size	Sch.	Thick(mm)	Q diam(mm)
Welded to:	Pipe	BS 10025 (50-B)	1.1	152.40	120	14.27	168.28
	Pipe	BS 10025 (50-B)	1.1	152.40	120	14.27	168.28
Joint type	Butt						

VARIABLES	Actual values	RANGE QUALIFIED
Type of weld joint	Pipe - Butt	Butt, Fillet welds and Branch welds where angle $\geq 60^\circ$
Base metal	1.1 to 1.1	1.1, 1.2, 1.4

BASE METAL THICKNESS	Butt	Fillet	Butt	Fillet
Plate thickness (mm)	14.27	-	5.00 min	5.00 min
Pipe/tube thickness (mm)	14.27	-	5.00 min	5.00 min
Pipe diameter (mm)	168.28	-	84.14 and above	84.14 and above

VARIABLES	Actual values	RANGE QUALIFIED
Welding process	111: MMA	111: MMA
Type	Manual	Manual
Backing	nb: without backing	ss nb, ss mb, bs
Filler metal type/designation	EN 499 E 46 6 Mn Ni B	Any Similar
Filler metal group	n/a	Any Similar
Covered electrode type	B basic	B, A, RA, RB, RC, RR, R
Weld deposit thickness (mm)	12.70	5.00 min
Weld position (Actual position tested)	H-L045	
Butt-Plate		PA, PC, PF, PE
Fillet-Plate		PA, PB, PF, PD
Butt-Pipe		PA, PF, PC, H-L045
Fillet-Pipe		PA, PB, PF, PD
Butt-Pipe Diameter (see EN287 5.3 a,c)		-

TESTS

Type of test	Acceptance criteria	Result	Comments
Visual examination per Table 10 and EN 970	EN ISO 5817	Acceptable	see - EN ISO 5817
Radiographic examination per Table 10 and EN 1435	EN ISO 5817	Acceptable	see - EN ISO 5817

Notes	branch set-on; angle at smallest required
-------	---

CERTIFICATION

Tests conducted by		Laboratory test number	
Mechanical tests by		Test file number	

We certify that the statements in this record are correct and that the test welds were prepared, welded and tested in accordance with the requirements of EN 287

Signature 1 (defined using Tools-Options-Default Settings)

Name	Signature	Name	Signature
Date		Date	

Signature 2 (also user defined)

Welderqual 4.6.000
Catalog n° WPQ00010

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Page 1 of 1

Figure 3 Example of a Welder Qualification Test Certificate (WPQ) to EN 287 format.

1 General

One of the duties of the Visual/Welding Inspector is to carry out materials inspection and there are a number of situations where the inspector will be required to do this:

- At the plate or pipe mill.
- During fabrication or construction of the material.
- After installation of material, usually during a planned maintenance programme, outage or shutdown.

A wide range of materials are available that can be used in fabrication and welding. These include, but are not limited to:

- Steels
- Stainless steels
- Aluminium and its alloys
- Nickel and its alloys
- Copper and its alloys
- Titanium and its alloys
- Cast iron

These materials are all widely used in fabrication, welding and construction to meet the requirements of a diverse range of applications and industry sectors.

There are three essential aspects to material inspection that the Inspector should consider:

- 1 Material type and weldability
- 2 Material traceability
- 3 Material condition and dimensions.

2 Material Types and Weldability

A Welding Inspector must be able to understand and interpret the material designation in order to check compliance with relevant normative documents. For example materials standards such as BS EN, API, ASTM, the welding procedure specification (WPS), the purchase order, fabrication drawings, the quality plan/the contract specification and client requirements.

A commonly used material standard for steel designation is **BS EN 10025 – Hot rolled products of non-alloy structural steels.**

A typical steel designation to this standard, S355J2G3, would be classified as follows:

S Structural steel
355 Minimum yield strength: N/mm² at t ≤ 16mm
J2 Longitudinal Charpy, 27Joules 6-20°C
G3 Normalised or normalised rolled

In terms of material type and weldability, commonly used materials and most alloys of these materials can be fusion welded using various welding processes, in a wide range of thickness, and, where applicable, diameters.

Reference to other standards such as ISO 15608 Welding - *Guidelines for a metallic material grouping system*, steel producer and welding consumable data books can also provide the Inspector with guidance on the suitability of a material and consumable type for a given application.

3 Alloying Elements and Their Effects

Iron	Fe	
Carbon	C	Strength
Manganese	Mn	Toughness
Silicon	Si	< 0.3% deoxidiser
Aluminium	Al	Grain refiner, <0.008% deoxidiser + toughness
Chromium	Cr	Corrosion resistance
Molybdenum	Mo	1% is for creep resistance
Vanadium	V	Strength
Nickel	Ni	Low temperature applications
Copper	Cu	Used for weathering steels (Corten)
Sulphur	S	Residual element (can cause hot shortness)
Phosphorus	P	Residual element
Titanium	Ti	Grain refiner, used as a micro-alloying element (strength and toughness)
Niobium	Nb	Grain refiner, used as a micro-alloying element (strength and toughness)

4 Material Traceability

Traceability is defined as ‘the ability to trace the history, application or location of that which is under consideration.’ In the case of a welded product, traceability may require the inspector to consider the:

- Origin of the materials – both parent and filler material.
- Processing history – for example before or after PWHT.
- Location of the product – this would usually refer to a specific part or sub-assembly.

In order to trace the history of the material, reference to the inspection documents must be made. *BS EN 10204 Metallic products – Types of inspection documents* is the standard, which provides guidance on these types of document. Under BS EN 10204 inspection documents fall into two types:

a) Non-specific inspection

Inspection carried out by the manufacturer in accordance with his own procedures to assess whether products defined by the same product specification and made by the same manufacturing process, are in compliance with the requirements of the order.

Type 2.1 are documents in which the manufacturer declares that the products supplied are in compliance with the requirements of the order **without inclusion of test results**.

Type 2.2 are documents in which the manufacturer declares that the products supplied are in compliance with the requirements of the order and in which **test results based on non-specific inspection are supplied**.

b) Specific inspection

Inspection carried out, before delivery, according to the product specification, on the products to be supplied or on test units of which the products supplied are part, in order to verify that these products are in compliance with the requirements of the order.

Type 3.1 are documents in which the manufacturer declares that the products supplied are in compliance with the requirements of the order and in which **test results are supplied**.

Type 3.2 are documents prepared by both the manufacturer’s authorised inspection representative independent of the manufacturing department, and either the purchaser’s authorised representative or the inspector designated by the official regulations, and in which they declare that the products supplied **are in compliance with the requirements of the order and in which test results are supplied**.

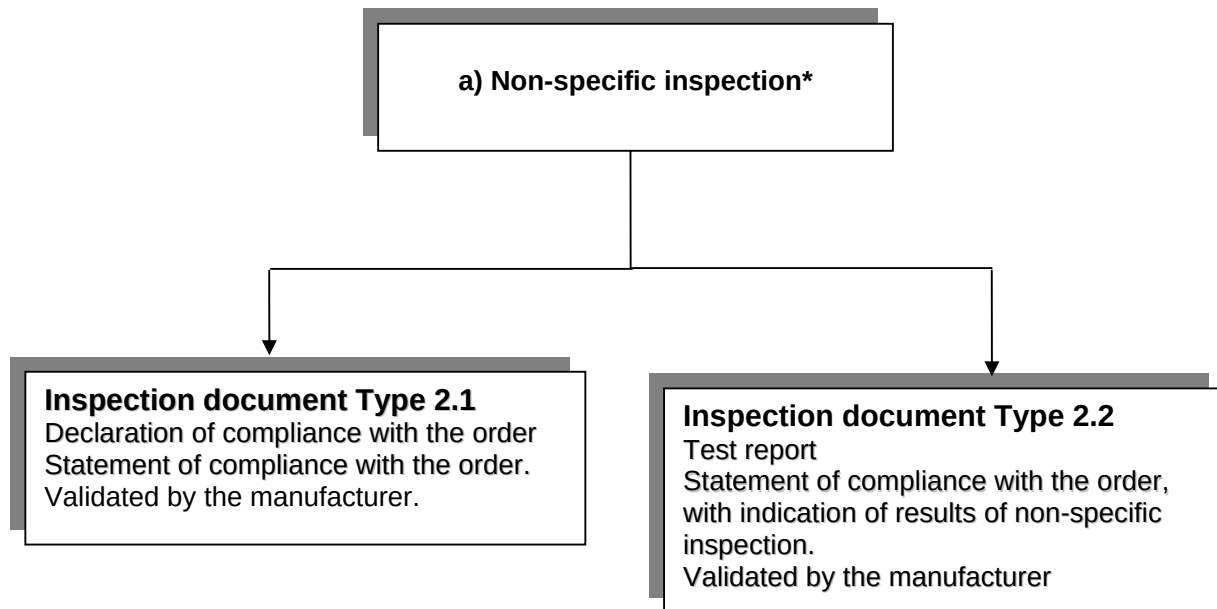
Application or location of a particular material can be carried out through a review of the Welding Procedure Specification (WPS), the fabrication drawings, the quality plan or by physical inspection of the material at the point of use.

In certain circumstances the inspector may have to witness the transfer of cast numbers from the original plate to pieces to be used in production.

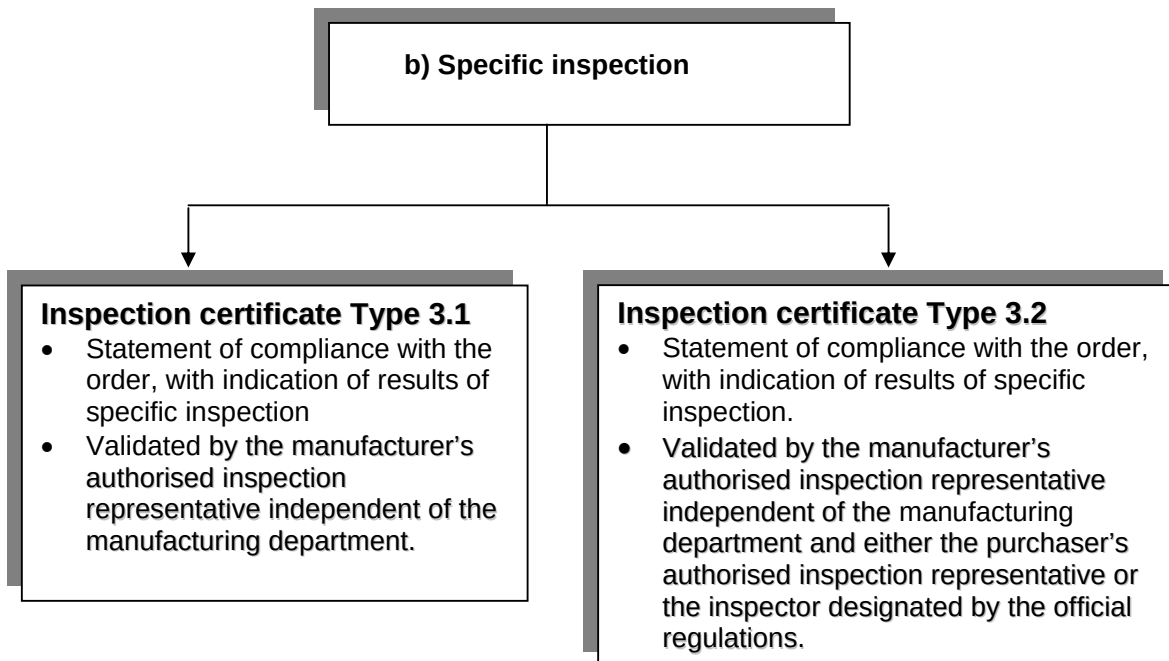
On pipeline work it is a requirement that the inspector records all the relevant information for each piece of linepipe. On large diameter pipes this information is usually stencilled on the inside of the pipe. On smaller diameter pipes the information may be stencilled along the outside of the pipe.

BS EN 10204: Metallic materials

Types of inspection documents summary



a) Non-specific inspection may be replaced by specific inspection if specified in the material standard or the order.



b) Quality management system of the material manufacturer certified by a competent body established within the community and having undergone a specific assessment for materials

5 Material Condition and Dimensions

The condition of the material could have an adverse effect on the service life of the component; it is therefore an important inspection point. The points for inspection must include:

- General inspection.
- Visible imperfections.
- Dimensions.
- Surface condition.

General inspection

This type of inspection takes account of storage conditions, methods of handling, the number of plates or pipes and distortion tolerances.

Visible imperfections

Typical visible imperfections are usually attributable to the manufacturing process and include cold laps, which break the surface or laminations if they appear at the edge of the plate. For laminations, which may be present in the body of the material, ultrasonic testing using a compression probe may be required.



Cold lap



Plate lamination

Dimensions

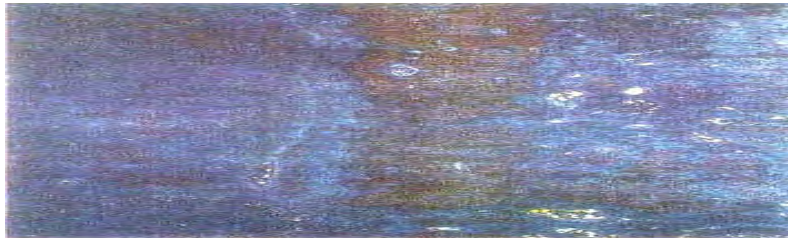
For plates this would include length, width and thickness.

For pipes, this would not only include length and wall thickness, but would also cover inspection of diameter and ovality. At this stage of the inspection the material cast or heat number may also be recorded for validation against the material certificate.

Surface condition

The surface condition of the material is important, it must not show excessive mill scale or rust, be badly pitted, or have unacceptable mechanical damage.

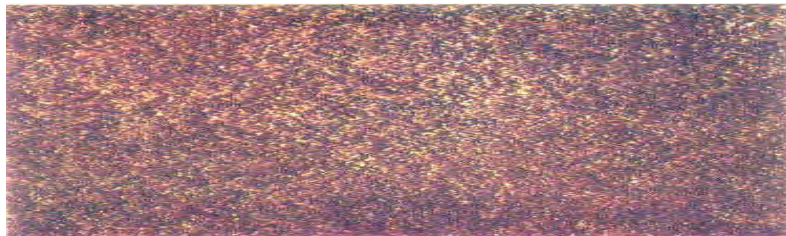
There are four grades of rusting which the inspector may have to consider:



Rust Grade A: Steel surface largely covered with adherent mill scale with little or no rust.



Rust Grade B: Steel surface, which has begun to rust, and from which mill scale has begun to flake.



Rust Grade C: Steel surface on which the mill scale has rusted away or from which it can be scraped. Slight pitting visible under normal vision.



Rust Grade D: Steel surface on which mill scale has rusted away. General pitting visible under normal vision.

6 Summary

Material inspection is an important part of the inspector's duties and an understanding of the documentation involved is the key to success.

Material inspection must be approached in a logical and precise manner if material verification and traceability are to be achieved. This can be difficult if the material is not readily accessible, access may have to be provided, safety precautions observed and authorisation obtained before material inspection can be carried out. Reference to the quality plan should identify the level of inspection required and the point at which inspection takes place. Reference to a fabrication drawing should provide information on the type and location of the material.

If material type cannot be determined from the inspection documents available, or if the inspection document is missing, other methods of identifying the material may need to be used.

These methods may include but are not limited to: spark test, spectroscopic analysis, chemical analysis, scleroscope hardness test, etc. These types of tests are normally conducted by an approved test house, but sometimes on site, and the inspector may be required to witness these tests in order to verify compliance with the purchase order or appropriate standard(s).

** EN ISO 9000 Quality management systems – Fundamentals and vocabulary*

1 General

It is not necessary for the Inspector to carry a wide range of codes and standards in the performance of his/her duties. Normally the specification or more precisely the contract specification is the only document required. However the contract specification may reference supporting codes and standards and the inspector should know where to access these *normative documents*.

The following is a list of definitions relating to codes and standards which the Inspector may come across whilst carrying out inspection duties.

2 Definitions

Normative document: A document that provides rules, guidelines or characteristics for activities or their results. The term *normative document* is a generic term, which covers documents such as standards, technical specifications, codes of practice and regulations.*

Standard: A document that is established by consensus and approved by a recognised body. A standard provides, for common and repeated use, guidelines, rules, characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context.*

Harmonised standards: Standards on the same subject approved by different standardising bodies, that establish interchangeability of products, processes and services, or mutual understanding of test results or information provided according to these standards.*

Code of practice: A document that recommends practices or procedures for the design, manufacture, installation, maintenance, utilisation of equipment, structures or products. A code of practice may be a standard, part of a standard or independent of a standard.*

Regulation: A document providing binding legislative rules that is adopted by an authority.*

Authority: A body (responsible for standards and regulations legal or administrative entity that has specific tasks and composition) that has legal powers and rights.*

Regulatory authority: Authority that is responsible for preparing or adopting regulations.*

Enforcement authority: Authority that is responsible for enforcing regulations.*

Specification: Document stating requirements. Meaningful data and its supporting medium stating needs or expectations that are stated, generally implied or obligatory.**

Procedure: Specified way to carry out an activity or a process*. Usually it is a written description of all essential parameters and precautions to be observed when applying a technique to a specific application following an established standard, code or specification.

Instruction: A written description of the precise steps to be followed, based on an established procedure, standard, code or specification.

Quality plan: A document specifying which procedures and associated resources shall be applied by whom and when to a specific project, product, process or contract.*

* ISO IEC Guide 2 – Standardisation and related activities – General vocabulary

** EN ISO 9000 – 2000 – Quality management systems – Fundamentals and vocabulary

3 Summary

Application standards and codes of practice ensure that a structure or component will have an acceptable level of quality and be fit for the intended purpose.

Applying the requirements of a standard, code of practice or specification can be a problem for the inexperienced inspector. Confidence in applying the requirements of one or all of these documents to a specific application only comes with use over a period of time.

If in doubt the inspector must always refer to a higher authority in order to avoid confusion and potential problems.

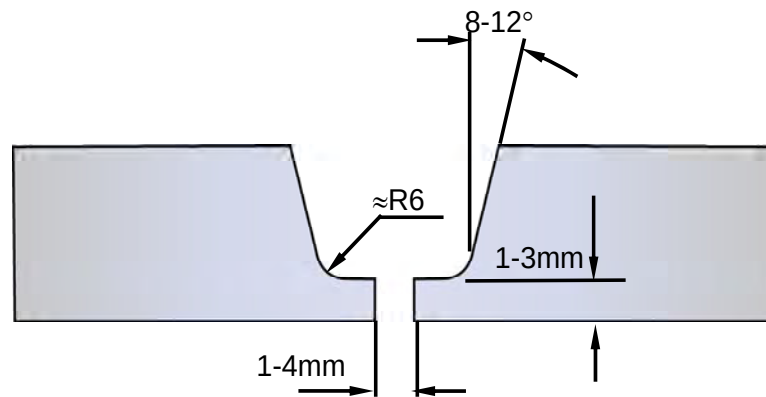
BS number	Title
BS 499: Part 1	Glossary of welding terms
BS 709	Methods of destructive testing fusion welded joints and weld metal in steel.
BS 1113	Specification for design and manufacture of water-tube steam generating plant.
BS 1453	Specification for filler materials for gas welding.
BS 1821	Specification for Class I oxyacetylene welding of ferritic steel pipe work for carrying fluids.
BS 2493	Low alloy steel electrodes for MMA welding.
BS 2633	Specification for Class I arc welding of ferritic steel pipe work for carrying fluids.
BS 2640	Specification for Class II oxyacetylene welding of carbon steel pipe work for carrying fluids.
BS 2654	Specification for manufacture of vertical steel welded non-refrigerated storage tanks with butt-welded shells for the petroleum industry.
BS 2901: Part 3	Filler rods and wires for copper and copper alloys.
BS 2926	Specification for chromium and chromium-nickel steel electrodes for MMA
BS 3019	TIG welding.
BS 3604	Steel pipes and tubes for pressure purposes; Ferritic alloy steel with specified elevated temperature properties for pressure purposes.
BS 3605	Specification for seamless tubes.
BS 4515	Specification for welding of steel pipelines on land and offshore.
BS 4570	Specification for fusion welding of steel castings.
BS 4677	Specification for arc welding of austenitic stainless steel pipe work for carrying fluids.
BS 4872 Part 1:	Approval testing of welders when procedure approval is not required. Fusion welding of steel.
BS 4872 Part 2:	TIG or MIG welding of aluminium and its alloys.
BS 6323	Specification for seamless and welded steel tubes for automobile, mechanical and general engineering purposes.
BS 6693	Method for determination of diffusible hydrogen in weld metal.
BS 6990	Code of practice for welding on steel pipes containing process fluids or their residues.
BS 7191	Specification for weldable structural steels for fixed offshore structures.
BS 7570	Code of practice for validation of arc welding equipment.

BS EN Number	Title
BS EN 287 Part 1:	Qualification test of welders - Fusion welding - Steels.
BS EN 440	Wire electrodes and deposits for gas shielded metal arc of non-alloy and fine grain steels.
BS EN 499	Covered electrodes for manual metal arc welding of non-alloy and fine grain steels.
BS EN 3834 - Parts 1 to 5	Quality requirements for fusion welding of metallic materials.
BS EN 756	Wire electrodes and flux wire combinations for submerged arc welding of non-alloy and fine grain steels.
BS EN 760	Fluxes for submerged arc welding.
BS EN 910	Destructive tests on welds in metallic materials-Bend tests.
BS EN 970	Non-destructive examination of fusion welds – visual examination.
BS EN 12072	Filler rods and wires for stainless steels.
BS EN ISO 18274	Aluminium and aluminium alloys and magnesium alloys. Nickel and nickel alloys.
Note: The inspector should have an awareness of the standards printed in bold.	

BS EN Number	Title
BS EN 1011 Part 1, Part 2, Part 3, Part 4.	Welding recommendations for welding of metallic materials. General guidance for arc welding. Arc welding of ferritic steels. Arc welding of stainless steels. Arc welding of aluminium and aluminium alloys.
EN 1320	Destructive tests on welds in metallic materials.
EN 1435	Non-destructive examination of welds – Radiographic examination of welded joints.
BS EN 10002	Tensile testing of metallic materials.
BS EN 10020	Definition and classification of grades of steel.
BS EN 10027	Designation systems for steels.
BS EN 10045	Charpy impact tests on metallic materials.
BS EN 10204	Metallic products – Types of inspection documents.
BS EN 22553	Welded, brazed and soldered joints – Symbolic representation on drawings.
BS EN 24063	Welding, brazing, soldering and braze welding of metal. Nomenclature of processes and reference numbers for symbolic representation on drawings.
BS EN 25817	Arc welded joints in steel. Guidance on quality levels for imperfections.
BS EN 26520	Classification of imperfections in metallic fusion welds, with explanations.
BS EN 26848	Specification for tungsten electrodes for inert gas shielded arc welding and for plasma cutting and welding.

ISO Number:	Title
ISO 857 - 1	Welding and allied processes – Vocabulary – Part 1 - Metal welding processes.
ISO 6947	Welds – Working positions – Definitions of angles of slope and rotation.
ISO 9606 - 2	Qualification test of welders – Fusion welding. Part 2 Aluminium and aluminium alloys.
ISO 15607	Specification and qualification of welding procedures for metallic materials – General rules.
ISO 15608	Welding – Guidelines for a metallic material grouping system.
ISO 15609 - 1	Specification and qualification of welding procedures for metallic materials – Welding procedure specification – Part 1: Arc welding.
ISO 15610	Specification and qualification of welding procedures for metallic materials. Qualification based on tested welding consumables.
ISO 15611	Specification and qualification of welding procedures for metallic materials. Qualification based on previous welding experience.
ISO 15613	Specification and qualification of welding procedures for metallic materials. Qualification based on pre-production-welding test.
ISO 15614	Specification and qualification of welding procedures for metallic Materials – Welding procedure test.
Part 1	Arc and gas welding of steels and arc welding of nickel and nickel alloys.
Part 2	
Part 3	Arc welding of aluminium and its alloys.*
Part 4	Welding procedure tests for the arc welding of cast irons.*
Part 5	Finishing welding of aluminium castings.*
Part 6	Arc welding of titanium, zirconium and their alloys.
Part 7	Copper and copper alloys.*
Part 8	Not used.
Part 9	Welding of tubes to tube-plate joints.
Part 10	Underwater hyperbaric wet welding.*
Part 11	Hyperbaric dry welding.*
Part 12	Electron and laser beam welding.
Part 13	Spot, seam and projection welding.*
	Resistance butt and flash welding.*
Note: The inspector should have an awareness of the standards printed in bold.	
*Proposed	

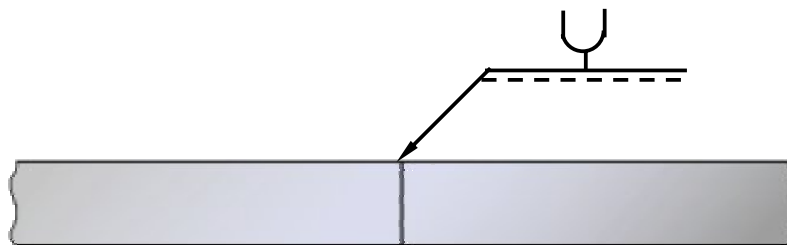
A weld joint can be represented on an engineering drawing by a detailed sketch showing every detail and dimension of the joint preparation – as shown below.



Single U preparation

While this method of representation gives comprehensive information, it can be time-consuming and overburden the drawing.

An alternative method is to use a symbolic representation to specify the required information – as shown below for the same joint detail.



Symbolic representation has the following advantages:

- Simple and quick to put on the drawing.
- Does not overburden the drawing.
- No need for an additional view – all welding symbols can be put on the main assembly drawing.

Symbolic representation has the following disadvantages:

- Can only be used for standard joints (eg BS EN ISO 9692).
- There is not a way of giving precise dimensions for joint details.
- Some training is necessary in order to interpret the symbols correctly.

1 Standards for Symbolic Representation of Welded Joints on Drawings

There are two principal standards that are used for welding symbols:

European Standard

EN 22553 – Welded, brazed & soldered joints – Symbolic representation on drawings

American Standard

AWS A2.4 – Standard Symbols for Welding, Brazing, & Non-destructive Examination

These standards are very similar in many respects, but there are also some major differences that need to be understood to avoid misinterpretation.

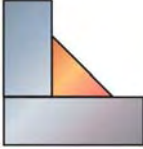
Details of the European Standard are given in the following sub-sections with only brief information about how the American Standard differs from the European Standard.

Elementary welding symbols

Various types of weld joint are represented by a symbol that is intended to help interpretation by being similar to the shape of the weld to be made.

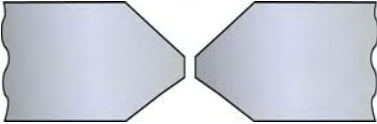
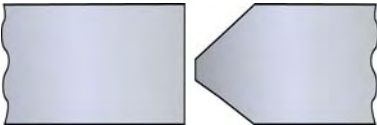
Examples of symbols used by EN 22553 are shown on the following pages.

2 Elementary Welding Symbols

Designation	Illustration of joint preparation	Symbol
Square butt weld		
Single V butt weld		∇
Single bevel butt weld		∇
Single V butt weld with broad root face		Y
Single bevel butt weld with broad root face		Y
Single U butt weld		U
Single J butt weld		J
Fillet weld		△
Surfacing (cladding)		3
Backing run (back or backing weld)		⌒
Backing bar		—

3 Combination of Elementary Symbols

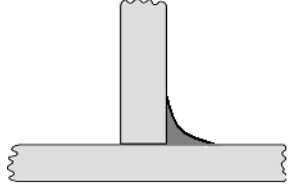
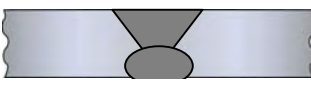
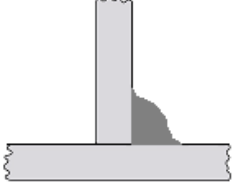
For symmetrical welds made from both sides, the applicable elementary symbols are combined – as shown below.

Designation	Illustration of joint preparation	Symbol
Double V butt weld (X weld)		
Double bevel butt weld (K weld)		
Double U butt weld		
Double J butt weld		

4 Supplementary Symbols

Weld symbols may be complemented by a symbol to indicate the required shape of the weld.

Examples of supplementary symbols and how they are applied are given below.

Designation	Illustration of joint preparation	Symbol
Flat (flush) single V butt weld		
Convex double V butt weld		
Concave fillet weld		
Flat (flush) single V butt weld with flat (flush) backing run		
Single V butt weld with broad root face and backing run		
Fillet weld with both toes blended smoothly		

Note: If the weld symbol does not have a supplementary symbol then the shape of the weld surface does not need to be indicated precisely.

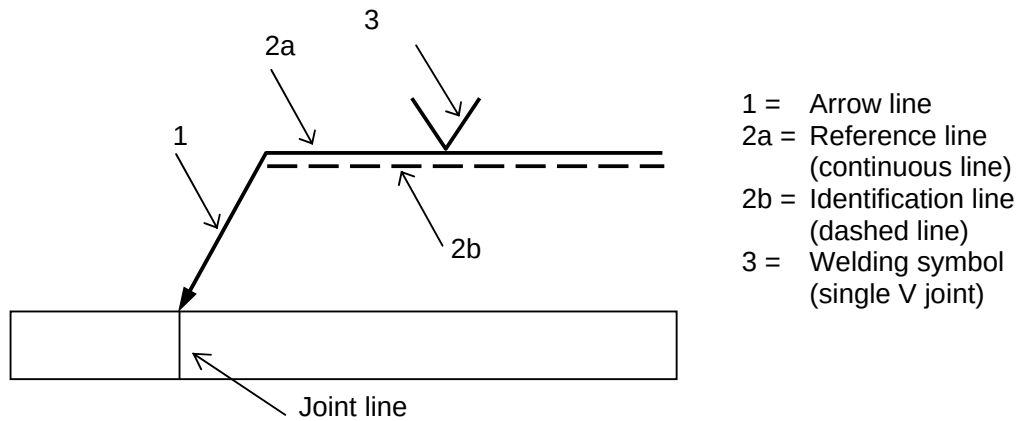
5 Position of Symbols on Drawings

In order to be able to provide comprehensive details for weld joints, it is necessary to distinguish the two sides of the weld joint.

This is done, according to EN 22553, by:

- An arrow line
- A dual reference line consisting of a continuous and a dashed line

The figure below illustrates the method of representation.



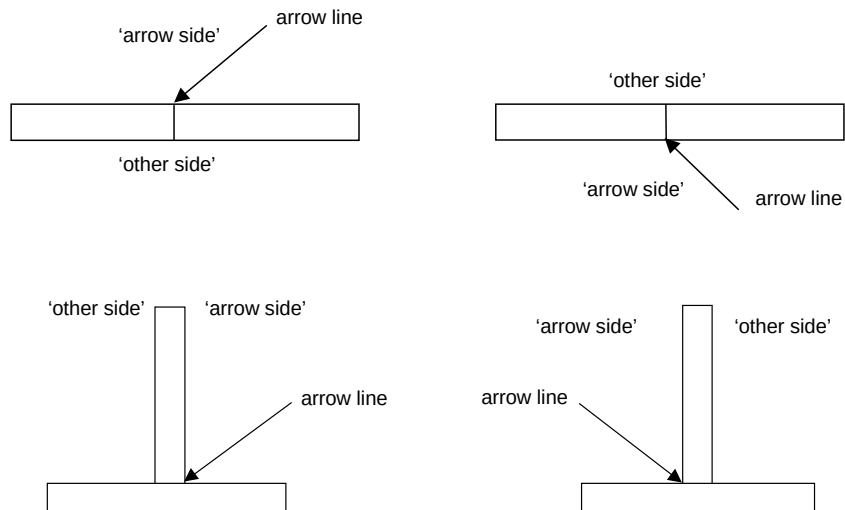
6 Relationship Between the Arrow and Joint Lines

One end of the joint line is called the **arrow side** and the opposite end is called **other side**.

The arrow side is always the end of the joint line that the arrow line points to (and touches).

It can be at either end of the joint line and it is the draughtsman who decides which end to make the arrow side.

The figure below illustrates these principles.



There are some conventions about the arrow line:

- It must touch one end of the joint line.
- It joins one end of the continuous reference line.
- In case of a **non-symmetrical joint**, such as a single bevel joint, the arrow line must point towards the joint member that will have the weld preparation put on to it (as shown below).

An example of how a single bevel butt joint should be represented.



7 Position of the Reference Line and Weld Symbol

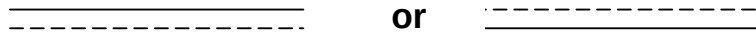
The reference line should, wherever possible, be drawn parallel to the bottom edge of the drawing (or perpendicular to it).

For a non-symmetrical weld it is essential that the arrow side and other side of the weld be distinguished. The convention for doing this is:

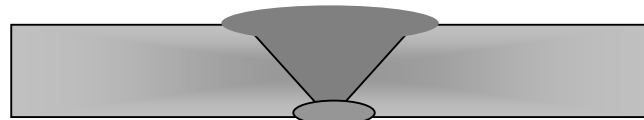
- Symbols for the weld details required on the arrow side must be placed on the continuous line.
- Symbols for the weld details on other side must be placed on the dashed line.

8 Positions of the Continuous and Dashed Lines

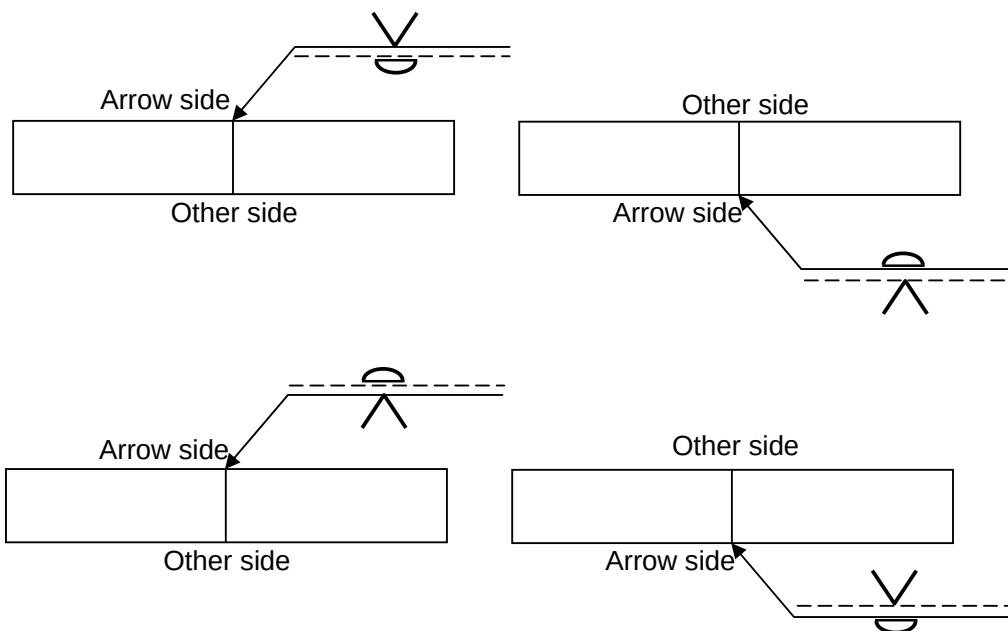
EN 22553 allows the dashed line to be either above or below the continuous line – as shown below.



If the weld is a symmetrical weld then it is not necessary to distinguish between the two sides and EN 22553 states that the dashed line should be omitted. Thus, a single V butt weld with a backing run can be shown by either of the four symbolic representations shown below.



Single V weld with backing run



Note: This flexibility of the position of the continuous and dashed lines is an interim measure that EN 22553 allows so that old drawings (to the obsolete BS 499 Part 2, for example) can be conveniently converted to show the EN method of representation.

9 Dimensioning of Welds

General rules

Dimensions may need to be specified for some types of weld and EN 22553 specifies a convention for this.

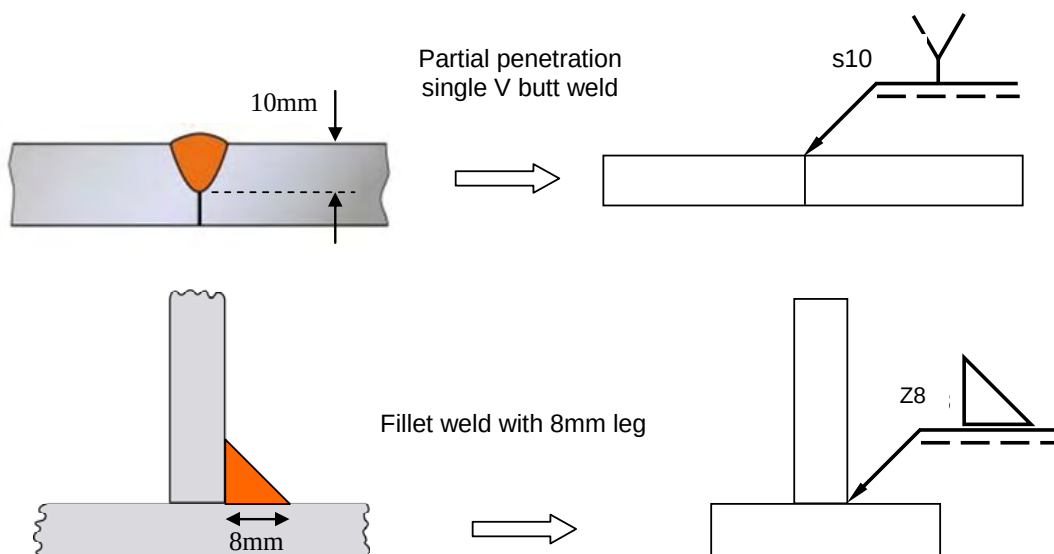
- Dimensions for the cross-section of the weld are written on the lefthand side of the symbol.
- Length dimensions for the weld are written on the righthand side of the symbol.
- Absence of any indication to the contrary, all butt welds are full penetration welds.

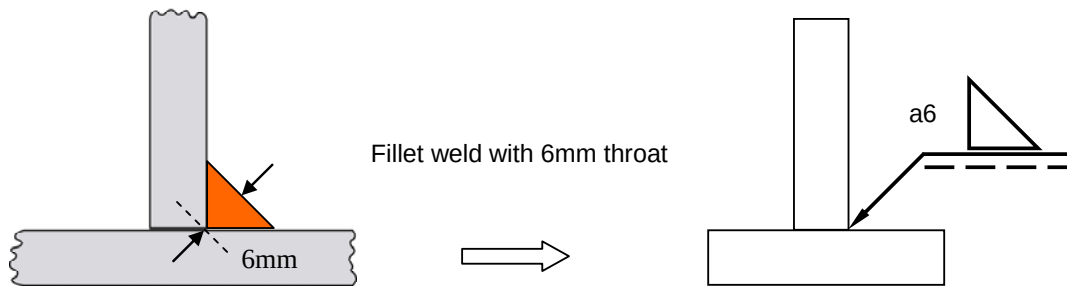
9.1 Symbols for cross-section dimensions

The following letters are used to indicate dimensions:

- a Fillet weld throat thickness.
- Z Fillet weld leg length.
- s Penetration depth.
(Applicable to partial penetration butt welds and deep penetration fillets.)

Some examples of how these symbols are used are shown below.





9.2 Symbols for length dimensions

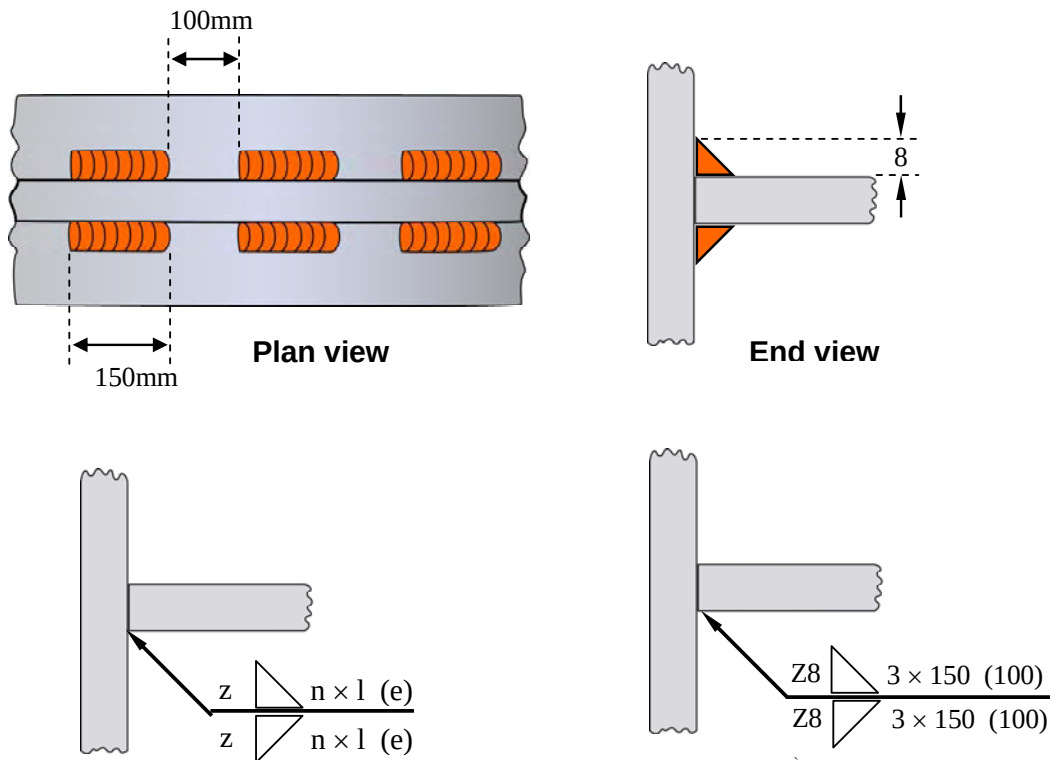
To specify weld length dimensions and, for intermittent welds the number of individual weld lengths (weld elements), the following letters are used:

l length of weld

(e) distance between adjacent weld elements

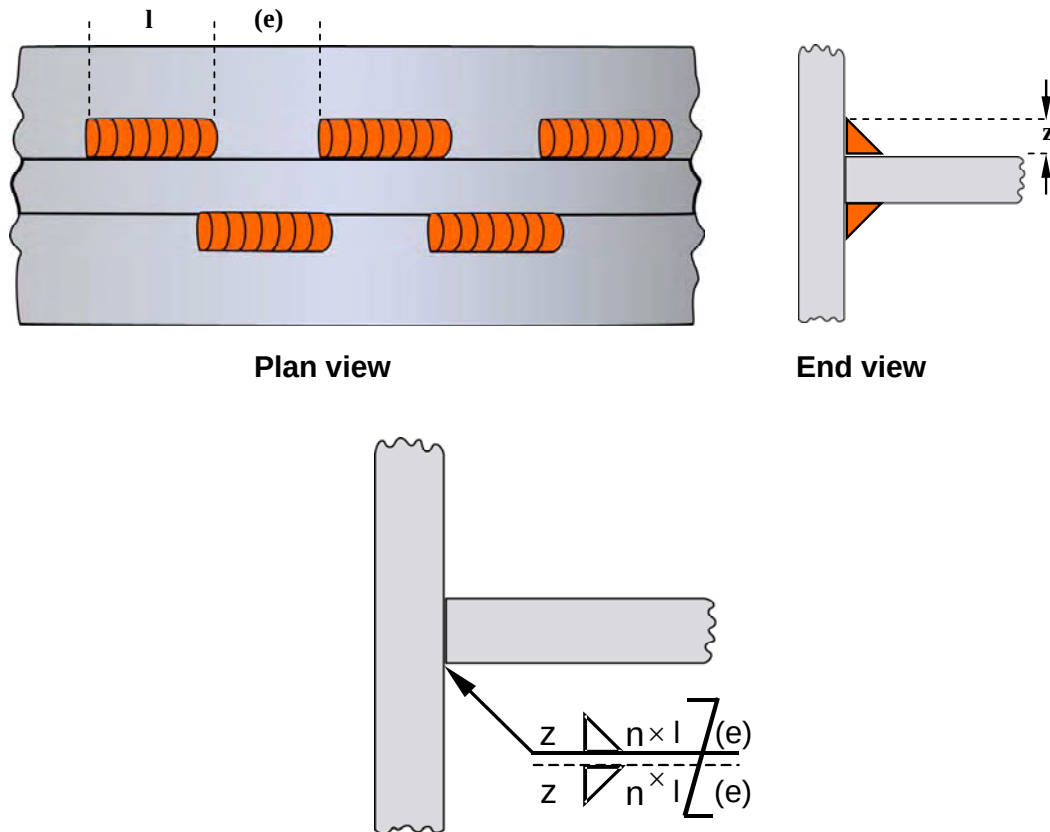
n number of weld elements

The use of these letters is illustrated for the intermittent double-sided fillet weld shown below.



Note: Dashed line not required because it is a symmetrical weld.

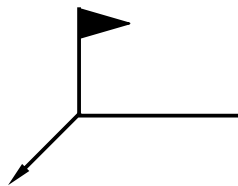
If an intermittent double-sided fillet weld is to be staggered, the convention for indicating this is shown below.



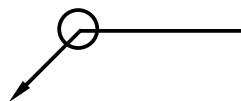
9.3 Complementary indications

Complementary indications may be needed to specify other characteristics of welds, eg:

- Field or site welds are indicated by a flag



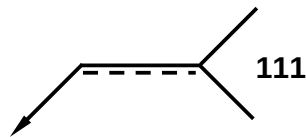
- A peripheral weld, to be made all around a part, is indicated by a circle



10 Indication of the Welding Process

If required, the welding process is symbolised by a number written between the two branches of a fork at the end of the reference line.

Some welding process designations

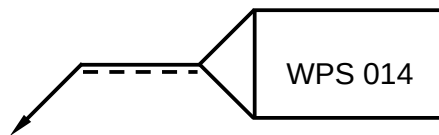


111 = MMA
121 = SAW
131 = MIG
135 = MAG

11 Other Information in the Tail of the Reference Line

In addition to specifying the welding process, other information can be added to an **open tail** (shown above) such as the NDT acceptance level the working position and the filler metal type and EN 22553 defines the sequence that must be used for this information.

A closed tail can also be used into which reference to a specific instruction can be added.



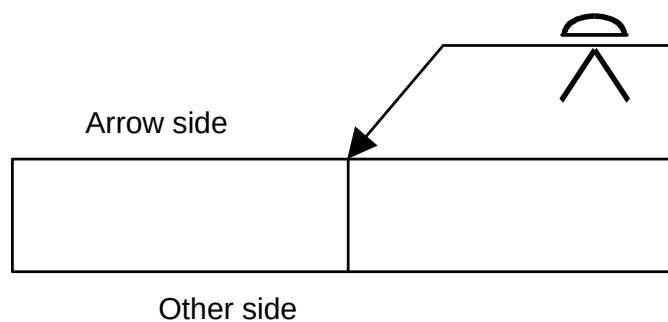
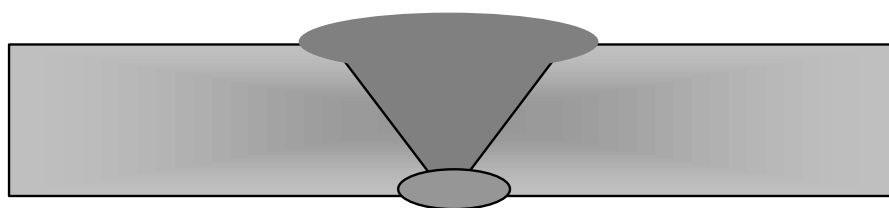
12 Weld Symbols in Accordance with AWS 2.4

Many of the symbols and conventions that are specified by EN 22553 are the same as those used by AWS.

The major differences are:

- Only one reference line is used (a continuous line)
- Symbols for weld details on the **arrow side** go **underneath the reference line**
- Symbols for weld details on the **other side** go **on top of the reference line**

These differences are illustrated by the following example.



Welding positions

PA	1G/1F	Flat/downhand
PB	2F	Horizontal-vertical
PC	2G	Horizontal
PD	4F	Horizontal-vertical (overhead)
PE	4G	Overhead
PF	3G / 5G	Vertical-up
PG	3G / 5G	Vertical-down
H-L045	6G	Inclined pipe (upwards)
J-L045	6G	Inclined pipe (downwards)

1 General

Common characteristics of the four main arc welding processes, MMA, TIG, MIG/MAG and SAW are:

- An arc is created when an electrical discharge occurs across the gap between an electrode and parent metal.
- The discharge causes a spark to form causing the surrounding gas to ionise.
- The ionised gas enables a current to flow across the gap between electrode and base metal thereby creating an arc.
- The arc generates heat for fusion of the base metal.
- With the exception of TIG welding, the heat generated by the arc also causes the electrode surface to melt and molten droplets can transfer to the weld pool to form a weld bead or run.
- Heat input to the fusion zone depends on the voltage, arc current and welding/travel speed.

2 Productivity

With most welding processes, welding in the PA (flat or 1G) position will result in the greatest weld metal deposition rate and therefore highest productivity.

For consumable electrode welding processes, the rate of transfer of molten metal to the weld pool is directly related to the welding current density (the ratio of the current to the diameter of the electrode).

For TIG welding, the higher the current, the more energy there is for fusion and thus the higher the rate at which the filler wire can be added to the weld pool.

3 Heat Input

Arc energy is the amount of heat generated in the welding arc per unit length of weld, and is usually expressed in kilojoules per millimetre length of weld (kJ/mm) Heat input (HI) for arc welding is calculated from the following formula:

$$\text{Arc energy (kJ/mm)} = \frac{\text{Volts} \times \text{Amps}}{\text{Travel speed (mm/sec)} \times 1000}$$

Heat input is the energy supplied by the welding arc to the work piece and is expressed in terms of arc energy x *thermal efficiency factor*.

The *thermal efficiency factor* is the ratio of heat energy introduced into the welding arc to the electrical energy consumed by the arc.

Heat input values into the weld for various processes can be calculated from the arc energy by multiplying by the following *thermal efficiency factors*;

SAW (wire electrode)	1.0
MMA (covered electrode)	0.8
MIG/MAG	0.8
FCAW (with or without gas shield)	0.8
TIG	0.6
Plasma	0.6

Example

A weld is made using the MAG welding process and the following welding conditions were recorded;

Volts: 24
Amps: 240
Travel speed: 300mm per minute

$$\begin{aligned}\text{Arc energy (kJ/mm)} &= \frac{\text{Volts} \times \text{Amps}}{\text{Travel speed (mm/sec)} \times 1000} \\ &= \frac{24 \times 240}{300 / 60 \times 1000} \\ &= \frac{5760}{5000} \\ \text{Arc energy} &= 1.152 \text{ or } 1.2 \text{ kJ/mm} \\ \text{Heat input} &= 1.2 \times 0.8 = 0.96 \text{ kJ/mm}\end{aligned}$$

Heat input is mainly influenced by the travel speed.

Welding position and the process have a major influence on the travel speed that can be used.

For manual and semi-automatic welding the following are general principles:

- Vertical-up progression tends to give the highest heat input because there is a need to weave to get suitable profile and the forward travel speed is relatively slow.
- Vertical-down welding tends to give the lowest heat input because of the fast travel speed that can be used.
- Horizontal-vertical welding is a relatively low heat input welding position because the welder cannot weave in this position.
- Overhead welding tends to give low heat input because of the need to use low current and relatively fast travel speed.
- Welding in the flat position (downhand) can be a low or high heat input position because the welder has more flexibility about the travel speed that can be used.
- Of the arc welding processes, SAW has potential to give the highest heat input and the highest deposition rates and TIG and MIG/MAG can produce very low heat input.
- Typical heat input values for controlled heat input welding will tend to be in the range ~ 1.0 to ~ 3.5 kJ/mm.

4 Welding Parameters

Arc voltage

Arc voltage is related to the arc length. For processes where the arc voltage is controlled by the power source (SAW, MIG/MAG and FCAW) and can be varied independently from the current, the voltage setting will affect the profile of the weld.

As welding current is raised, the voltage also needs to be raised to spread the weld metal and produce a wider and flatter deposit.

For MIG/MAG, arc voltage has a major influence on droplet transfer across the arc.

Welding current

Welding current has a major influence on the depth of fusion/penetration into the base metal and adjacent weld runs.

As a general rule, the higher the current the greater the depth of penetration.

Penetration depth affects dilution of the weld deposit by the parent metal and it is particularly important to control this when dissimilar metals are joined.

Polarity

Polarity determines whether most of the arc energy (the heat) is concentrated at the electrode surface or at the surface of the parent material.

The location of the heat with respect to polarity is not the same for all processes and the effects/options/benefits for each of the main arc welding processes are summarised below:

Process	Polarity		
	DC +ve	DC -ve	AC
MMA	Best penetration	Less penetration but higher deposition rate (used for root passes and weld overlaying)	Not suitable for some electrodes. Minimises arc blow.
TIG	Rarely used due to tungsten overheating	Used for all metals – except Al/Al alloys (and Mg/Mg alloys)	Required for Al/Al alloys to break-up the refractory oxide film
GMAW solid wires (MIG/MAG)	Used for all metals and virtually all situations	Rarely used	Not used
FCAW/MCAW gas-shielded and self-shielded cored wires	Most common	Some positional basic fluxed wires are designed to run on -ve; some metal cored wires may also be used on -ve particularly for positional welding	Not used
SAW	Best penetration	Less penetration but higher deposition rate (used for root passes and overlaying)	Used to avoid arc blow – particularly for multi-electrode systems

5 Power Source Characteristics

In order to strike an arc, a relatively high voltage is required to generate a spark between the electrode and base metal. This is known as the open circuit voltage (OCV) and it is typically in the range from ~50 to ~90V.

Once an arc has been struck and stabilised, there is a relationship between the arc voltage and the current flowing through the welding circuit that depends on the electrical characteristics of the power source.

This relationship is known as the power source static characteristic and power sources are manufactured to give a **constant current** or a **constant voltage** characteristic.

5.1 Constant current power source

This is the preferred type of power source for manual welding (MMA and manual TIG).

The Volt-Amp relationship for a constant current power source is shown in Figure 1. This shows the no current position (the OCV) and from this point there are arc voltage/current curves that depend for the various current settings on the power source.

For manual welding (MMA and manual TIG) the welder sets the required current on the power source, but arc voltage is controlled by the arc length that the welder uses.

A welder has to work within a fairly narrow range of arc length for a particular current setting – if it is too long the arc will extinguish and if it is too short the electrode may stub into the weld pool and the arc will be extinguished.

For the operating principle of this type of power source see Figure 1.

The welder tries to hold a fairly constant arc length (B in Figure 1) for the current (Y) that has been set. However, he cannot keep the arc length constant and it will vary over a small working range (A to C in Figure 1) due to normal hand movement during welding.

The power source is designed to ensure that these small changes in arc voltage during normal welding will give only small changes in current (X to Z). Thus, the current can be considered to be essentially constant and this ensures that the welder is able to maintain control of fusion.

The drooping shape of the Volt-Amp curves has led to constant current power sources sometimes being referred to as having a '**drooping**' characteristic.

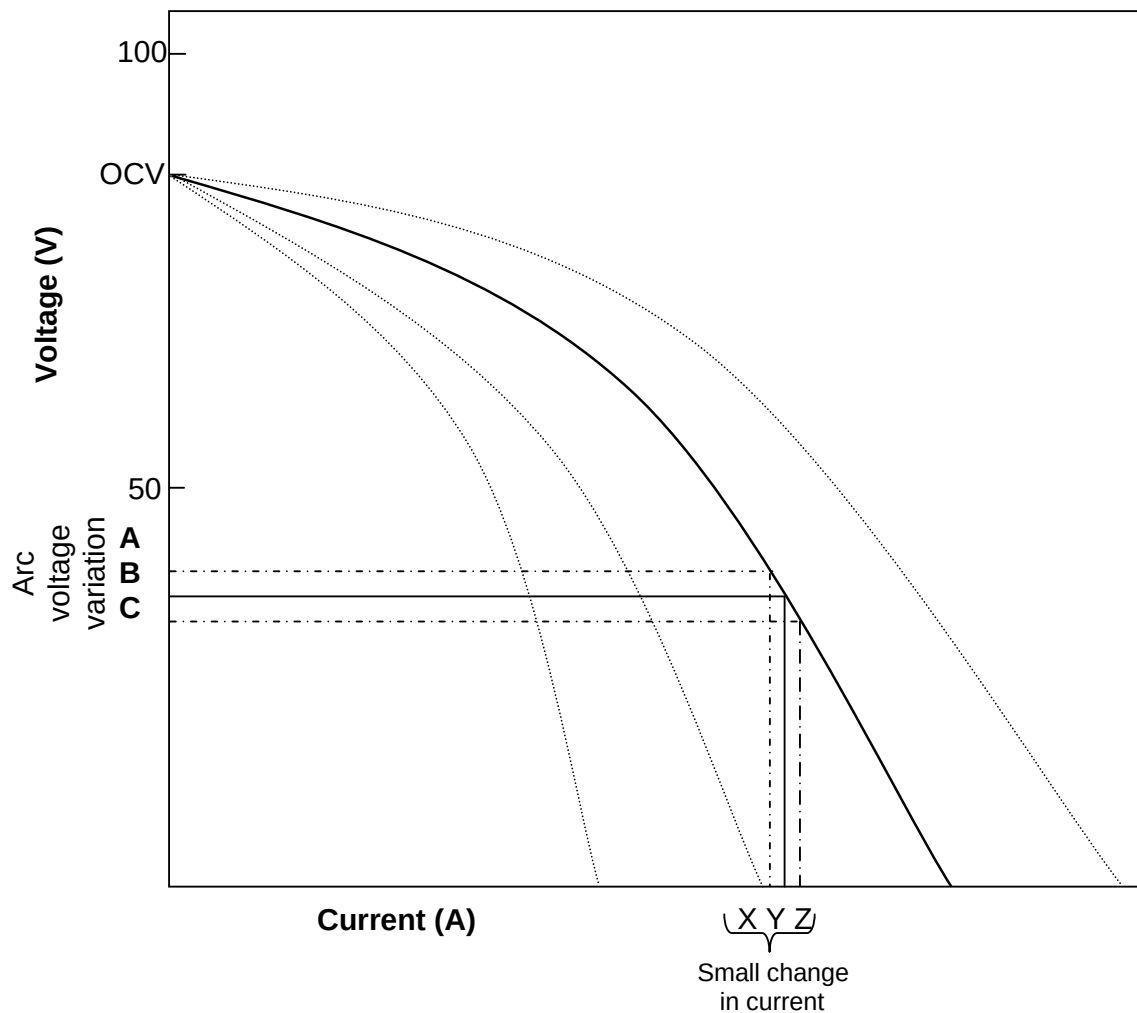


Figure 1 Typical Volt-Amp curves for a constant current power source.

5.2 Constant voltage power source

This is the preferred type of power source for welding processes that have a wire feeder (MIG/MAG, FCAW and SAW).

Wire feed speed and current are directly related so that as the current is increased, so does the feed speed and there is a corresponding increase in the burn-off rate to maintain the arc length/ voltage.

The operating principle of this type of power source is shown in Figure 2

A welder sets the voltage B and the current Y on the power source. If the arc length is decreased to C (due to a variation in weld profile or as the welder's hand moves up and down during semi-automatic welding) there will be a momentary increase in welding current to Z. The higher current Z, gives a higher burn-off rate and this brings the arc length (and arc voltage) back to the pre-set value.

Similarly, if the arc length increases the current quickly falls to X and the burn-off rate is reduced so that the arc length is brought back to the pre-set level B.

Thus, although the arc voltage does vary a little during welding the changes in current that restore the voltage to the pre-set value happen extremely quickly so that the voltage can be considered to remain constant.

The straight-line relationship between voltage and current and the relatively small gradient is the reason why this type of power source is often referred to as having a '**flat characteristic**'.

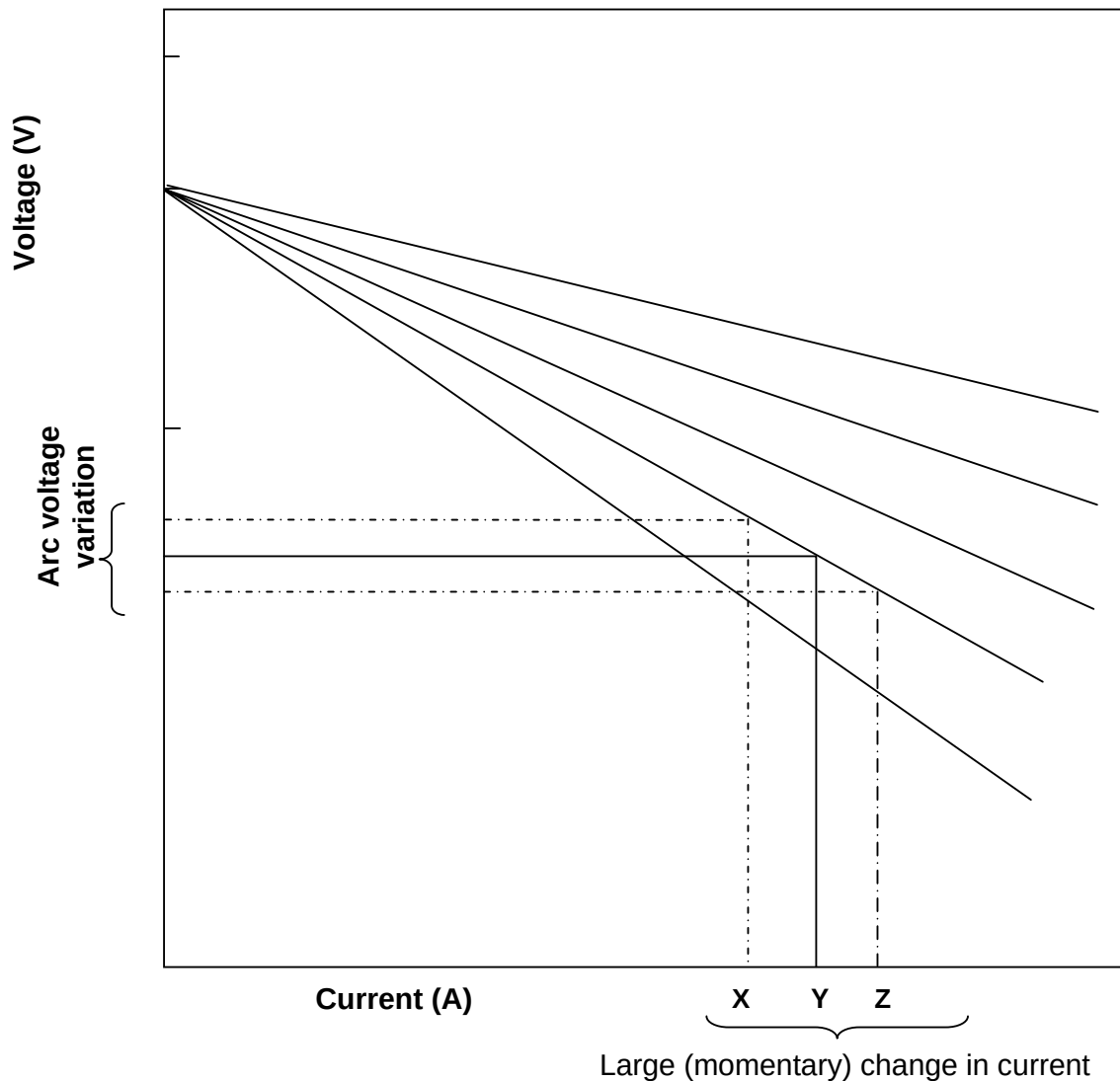


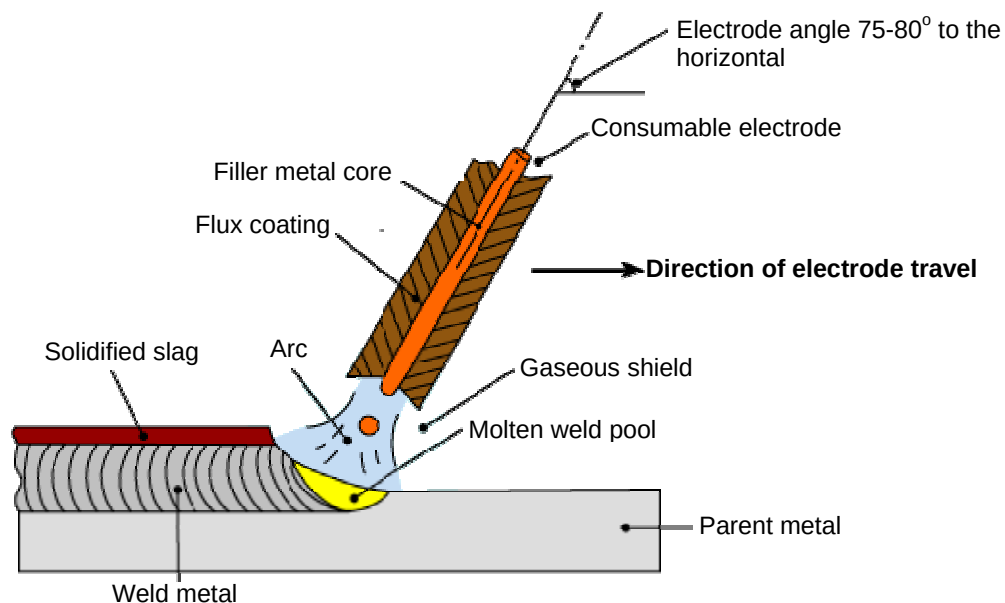
Figure 2 Typical Volt-Amp curves for a constant voltage power source.

1 Manual Metal Arc/Shielded Metal Arc Welding (MMA/SMAW)

Manual metal arc welding (MMA) was invented in Russia in 1888. It involved a bare metal rod with no flux coating to give a protective gas shield. The development of coated electrodes did not occur until the early 1900s, when the Kjellberg process was invented in Sweden and the quasi-arc method was introduced in the UK.

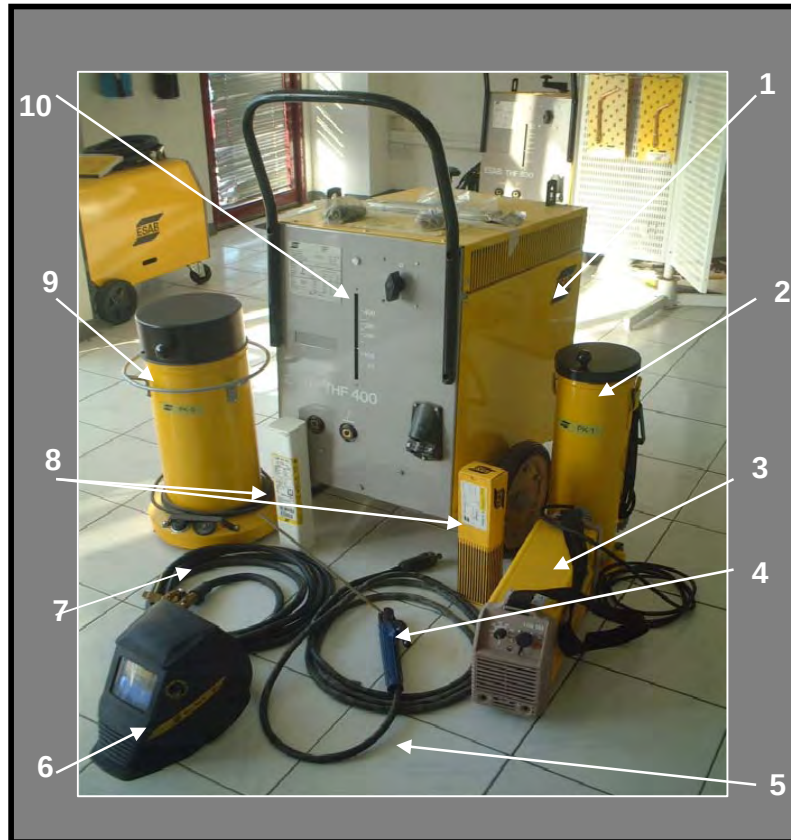
The most versatile of the welding processes, MMA welding is suitable for welding most ferrous and non-ferrous metals, over a wide range of thicknesses. It can be used in all positions, with reasonable ease of use and relatively economically. The final weld quality is primarily dependent on the skill of the welder.

When an arc is struck between the coated electrode and workpiece, both the electrode and workpiece surface melt to form a weld pool. The average temperature of the arc is approximately 6000°C, which is sufficient to simultaneously melt the parent metal, consumable core wire and flux coating. The flux forms gas and slag, which protect the weld pool from oxygen and nitrogen in the surrounding atmosphere. The molten slag solidifies, cools and must be chipped off the weld bead once the weld run is complete (or before the next weld pass is deposited). The process allows only short lengths of weld to be produced before a new electrode needs to be inserted in the holder.



The manual metal arc welding process.

2 Manual Metal Arc Welding Basic Equipment Requirements



- 1) **Power source transformer/rectifier** (*constant current type*)
- 2) **Holding oven** (*holds at temperatures up to 150°C*)
- 3) **Inverter power source** (*more compact and portable*)
- 4) **Electrode holder** (*of a suitable amperage rating*)
- 5) **Power cable** (*of a suitable amperage rating*)
- 6) **Welding visor** (*with correct rating for the amperage/process*)
- 7) **Power return cable** (*of a suitable amperage rating*)
- 8) **Electrodes** (*of a suitable type and amperage rating*)
- 9) **Electrode oven** (*bakes electrodes at up to 350°C*)
- 10) **Control panel** (*on/off/amperage/polarity/OCV*)

3 Power Requirements

Manual metal arc welding can be carried out using either direct (DC) or alternating (AC) current. With DC welding current either positive (+ve) or negative (-ve) polarity can be used, so current is flowing in one direction. AC welding current flows from negative to positive, and is two directional.

Power sources for MMA welding are either transformers (which transform mains AC to AC suitable for welding), transformer-rectifiers (which rectify AC to DC), diesel or petrol driven generators (preferred for site work) or inverters (a more recent addition to welding power sources). For MMA welding a power source with a constant current (drooping) output must be used.

The power source must provide:

- An open circuit voltage (OCV) to initiate the arc, between 50 and 90V.
- Welding voltage to maintain the arc during welding, between 20 and 30V
- Suitable current range, typically 30-350 amps
- Stable arc-rapid arc recovery or arc re-ignition without current surge.
- Constant welding current. The arc length may change during welding, but consistent electrode burn-off rate and weld penetration characteristics must be maintained during welding.

4 Welding Variables

Other factors, or welding variables, which affect the final quality of the MMA weld, are:

Current (amperage)	} Affects heat input
Voltage	
Travel speed	
Polarity	
Type of electrode	



Examples of the MMA welding process

4.1 Current (amperage)

The flow of electrons through the circuit is the welding current, measured in Amperes (I). Amperage controls burn-off rate and depth of penetration. Welding current level is determined by the size of electrode - manufacturers recommend the normal operating range and current

Incorrect amperage settings when using MMA can contribute to the following:

Amperage too low: Poor fusion or penetration, irregular weld bead shape, slag inclusion unstable arc, arc stumble, porosity, potential arc strikes.

Amperage too high: Excessive penetration, burn through, undercut, spatter, porosity, deep craters, electrode damage due to overheating, high deposition making positional welding difficult.

4.2 Voltage

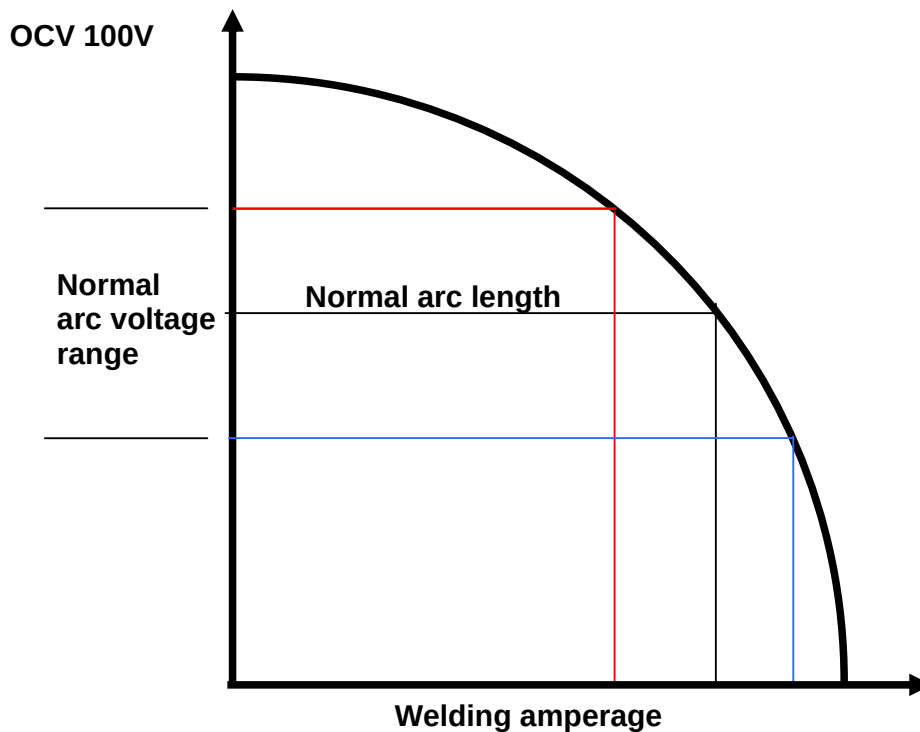
Welding potential or pressure required for current to flow through the circuit is the voltage (U). For MMA welding the voltage required to initiate the arc is OCV, which is the voltage measured between the output terminals of the power source when no current is flowing through the welding circuit.

For safety reasons the OCV should not exceed 100V, and is usually between 50-90V. Arc voltage is the voltage required to maintain the arc during welding and is usually between 20-40V. Arc voltage is a function of arc length. With MMA the welder controls the arc length and therefore the arc voltage. Arc voltage controls weld pool fluidity.

The effects of having the wrong arc voltage can be:

Arc voltage too low: Poor penetration, electrode stubbing, lack of fusion defects, potential for arc strikes, slag inclusion, unstable arc condition, irregular weld bead shape.

Arc voltage too high: Excessive spatter, porosity, arc wander, irregular weld bead shape, slag inclusions, fluid weld pool making positional welding difficult.



Constant current (drooping) output characteristic

Large change in arc voltage =
small change in welding amperage $\pm 10V = \pm 5 \text{ amps}$

4.3 Travel speed

Travel speed is the rate of weld progression, the third factor that affects heat input and therefore metallurgical and mechanical conditions. The potential defects associated with incorrect welding speeds when using the MMA welding process are:

Travel speed too fast: Narrow thin weld bead, fast cooling, slag inclusions, undercut, poor fusion/penetration.

Travel speed too slow: Cold lap, excess weld deposition, irregular bead shape undercut.

4.4 Polarity (type of current)

Polarity will determine the distribution of heat energy at the welding arc. The preferred polarity of the MMA system depends primarily upon the electrode being used and the desired properties of the weld.

Direct current (DC)

Direct current is the flow of current in one direction. For MMA welding it refers to the polarity of the electrode.

Direct current/electrode positive (DCEP/DC+)

When the electrode is on the positive pole of the welding circuit, the workpiece becomes the negative pole. Electron flow direction is from the workpiece to the electrode.

When the electrode is positively charged (DCEP) and the workpiece is negatively charged this has the effect of generating two thirds of the available heat energy at the tip of the electrode, with the remaining one third being generated in the parent material, this will result in an increase in the depth of the weld penetration.

Direct current/electrode negative (DCEN/DC-)

When the electrode is on the negative pole of the welding circuit, the workpiece becomes the positive pole. Electron flow direction is from the electrode to the workpiece. The distribution of energy is now reversed. One third of the available heat energy is generated at the tip of the electrode, the remaining two thirds in the parent material.

Direct current with a negatively charged electrode (DCEN) causes heat to build up on the electrode, increasing the electrode melting rate and decreasing the depth of the weld penetration.

The welding arc when using direct current can be affected by arc blow, the deflection of the arc from its normal path due to magnetic forces.

Alternating current (AC)

The current alternates in the welding circuit, flowing first in one direction and then the other. With alternating current, the direction of flow changes 100-120 times per second, 50-60 cycles per second (cps). Alternating current is the flow of current in two directions.

Therefore, distribution of heat energy at the arc is equal, 50% at the electrode, 50% at the workpiece.

4.5 Type of consumable electrode

For MMA welding there are three generic types of flux covering:

Rutile electrodes contain a high proportion of titanium oxide (rutile) in the coating. Titanium oxide promotes easy arc ignition, smooth arc operation and low spatter. These electrodes are general purpose electrodes with good welding properties. They can be used with AC and DC power sources and in all positions. The electrodes are especially suitable for welding fillet joints in the horizontal/vertical (HV) position.

Features:

- Moderate weld metal mechanical properties
- Good bead profile produced through the viscous slag
- Positional welding possible with a fluid slag (containing fluoride)
- Easily removable slag

Basic electrodes contain a high proportion of calcium carbonate (limestone) and calcium fluoride (fluorspar) in the coating. This makes the slag coating more fluid than rutile coatings - this is also fast freezing which assists welding in the vertical and overhead position. These electrodes are used for welding medium and heavy section fabrications where higher weld quality, good mechanical properties and resistance to cracking (due to high restraint) are required.

Features:

- Low hydrogen weld metal
- Requires high welding currents/speeds
- Poor bead profile (convex and coarse surface profile)
- Slag removal difficult

Cellulosic electrodes contain a high proportion of cellulose in the coating and are characterised by a deeply penetrating arc and a rapid burn-off rate giving high welding speeds. Weld deposit can be coarse and with fluid slag, deslagging can be difficult. These electrodes are easy to use in any position and are noted for their use in the stovepipe welding technique.

Features:

- Deep penetration in all positions
- Suitability for vertical-down welding
- Reasonably good mechanical properties
- High level of hydrogen generated - risk of cracking in the heat affected zone (HAZ)

It should be noted that within these three generic groups there are sub-groups of covered electrodes providing a wide range of electrode choice.

MMA electrodes are designed to operate with alternating current (AC) and direct current (DC) power sources. Although AC electrodes can be used on DC, not all DC electrodes can be used with AC power sources.

Operating factor: (O/F) The percentage (%) of **arc on time** in a given time span.

When compared with semi-automatic welding processes MMA has a low O/F of approximately 30%. Manual semi-automatic MIG/MAG O/F is about 60% with fully automated in the region of 90% O/F. A welding process **OF** can be directly linked to **productivity**.

Operating factor should not to be confused with the term **duty cycle**, which is a safety value given as the % of time a conductor can carry a current and is given as a specific current at **60** and **100%** of 10 minutes ie 350A 60% and 300A 100%

5 Summary of MMA/SMAW

Equipment requirements

- Transformer/rectifier, generator, inverter (constant amperage type)
- Power and power return cable (of a suitable amperage rating)
- Electrode holder (of a suitable amperage rating)
- Electrodes (of a suitable type and amperage rating)
- Correct visor/glass, safety clothing and good extraction

Parameters and inspection points

- Amperage
- Open circuit voltage(OCV)
- AC/DC and polarity
- Speed of travel
- Electrode type and diameter
- Duty cycles
- Electrode condition
- Connections
- Insulation/extraction
- Any special electrode treatment

Typical welding imperfections

- **Slag inclusions** caused by poor welding technique or insufficient inter-run cleaning.
- **Porosity** from using damp or damaged electrodes or when welding contaminated or unclean material.
- **Lack of root fusion or penetration** caused by incorrect settings of the amps, root gap or face width.

- **Undercut** caused by too high amperage for the position or by a poor welding technique eg travel speed too fast or slow, arc length (therefore voltage) variations particularly during excessive weaving.
- **Arc strikes** caused by incorrect arc striking procedure, or lack of skill. These may be also caused by incorrectly fitted/secured power return lead clamps.
- **Hydrogen cracks** caused by the use of incorrect electrode type or baking procedure and/or control of basic coated electrodes.

Successful welding with the MMA process is reliant on a number of factors, not least of which is the skill required to produce a sound weld. This is dependent on the welder's ability to match the arc length (the distance from the tip of the electrode to the workpiece), to the burn-off rate (the rate at which the electrode is consumed).

Advantages and disadvantages

Advantages

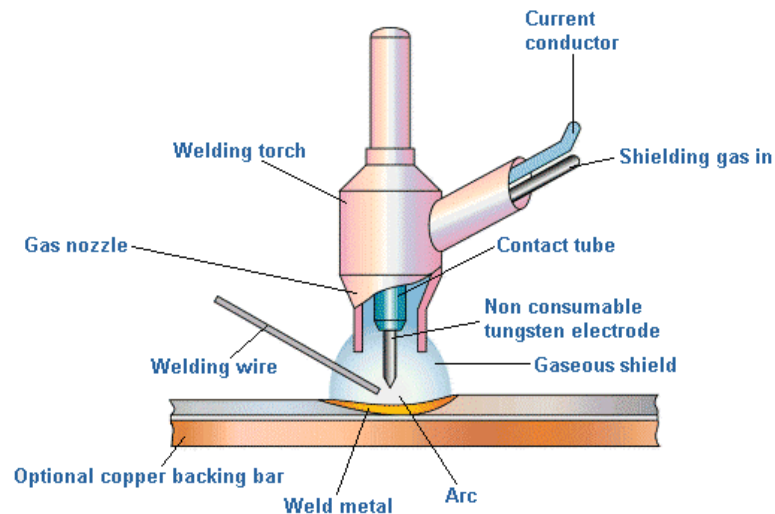
- Field or shop use
- Range of consumables
- All positional
- Very portable
- Simple equipment

Disadvantages

- High skill factor required
- Arc strikes/slag inclusions
- Low operating factor
- High level of generated fumes
- Hydrogen control

1 Process Characteristics

In the USA the TIG process is also called gas tungsten arc welding (GTAW). TIG welding is a process where melting is produced by heating with an arc struck between a non-consumable tungsten electrode and the workpiece. An inert gas is used to shield the electrode and weld zone to prevent oxidation of the tungsten electrode and atmospheric contamination of the weld and hot filler wire (as shown below).



Manual TIG welding

Tungsten is used because it has a melting point of 3370°C , which is well above any other common metal.

2 Process Variables

The main variables in TIG welding are:

- Welding current
- Current type and polarity
- Travel speed
- Shape of tungsten electrode tip and vertex angle
- Shielding gas flow rate
- Electrode extension

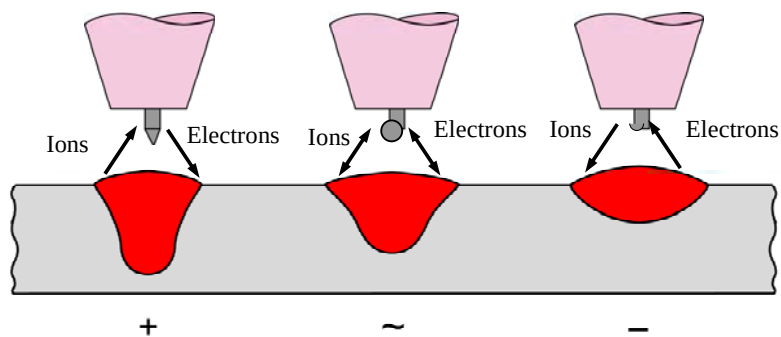
Each of these variables is considered in more detail in the following sub-sections.

2.1 Welding current

- Weld penetration is directly related to welding current
- If the welding current is too low, the electrode tip will not be properly heated and an unstable arc may result
- If the welding current is too high, the electrode tip might overheat and melt, leading to tungsten inclusions

2.2 Current type and polarity

- The best welding results are usually obtained with DC electrode negative
- Refractory oxides such as those of aluminium or magnesium can hinder fusion but these can be removed by using AC or DC electrode positive
- With a DC positively connected electrode, heat is concentrated at the electrode tip and therefore the electrode needs to be of greater diameter than when using DC negative if overheating of the tungsten is to be avoided. A water cooled torch is recommended if DC positive is used
- The current carrying capacity of a DC positive electrode is about one tenth that of a negative one and it is therefore limited to welding sections



Current type/polarity	DCEN	AC	DCEP
Heat balance	70% at work 30% at electrode	50% at work 50% at electrode	30% at work 70% at electrode
Weld profile	Deep, narrow	Medium	Shallow, wide
Cleaning action	No	Yes – every half cycle	Yes
Electrode capacity	Excellent (3.2mm/400A)	Good (3.2mm/225A)	Poor (6.4mm/120A)

2.3 Travel speed

- Travel speed affects both weld width and penetration but the effect on width is more pronounced.
- Increasing the travel speed reduces the penetration and width
- Reducing the travel speed increases the penetration and width

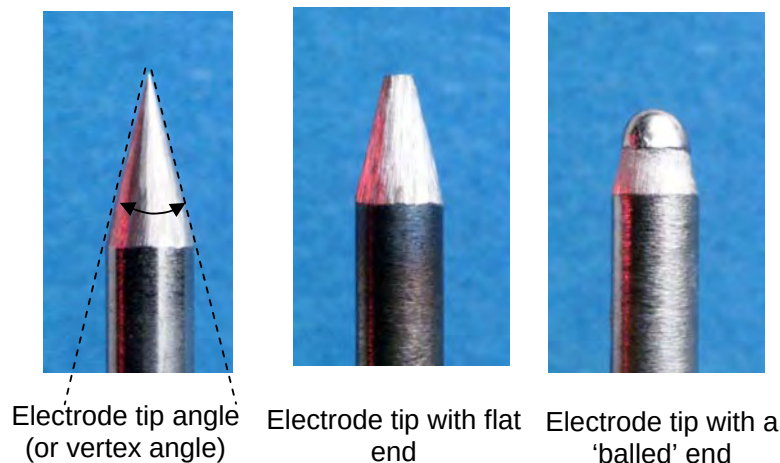
2.4 Tungsten electrode types

Different types of tungsten electrodes can be used to suit different applications:

- **Pure tungsten** electrodes are used when welding light metals with AC because of their ability to maintain a clean balled end. However they possess poor arc initiation and stability in AC mode compared with other types
- **Thoriated electrodes** are alloyed with thorium oxide (thoria) to improve arc initiation. They have higher current carrying capacity than pure tungsten electrodes and maintain a sharp tip for longer. Unfortunately, thoria is slightly radioactive (emitting α radiation) and the dust generated during tip grinding should not be inhaled. Electrode grinding machines used for thoriated tungsten grinding should be fitted with a dust extraction system.
- **Ceriated and lanthanated electrodes** are alloyed with cerium and lanthanum oxides, for the same reason as thoriated electrodes. They operate successfully with DC or AC but since cerium and lanthanum are not radioactive, these types have been used as replacements for thoriated electrodes
- **Zirconiated electrodes** are alloyed with zirconium oxide. Operating characteristics of these electrodes fall between the thoriated types and pure tungsten. However, since they are able to retain a balled end during welding, they are recommended for AC welding. Also, they have a high resistance to contamination and so are used for high integrity welds where tungsten inclusions must be avoided.

2.5 Shape of tungsten electrode tip

- With DC electrode negative, thoriated, ceriated or lanthanated tungsten electrodes are used with the end ground to a specific angle (the electrode tip or vertex angle – shown below).
- As a general rule, the length of the ground portion of the tip of the electrode should have a length equal to approximately 2 to 2.5 times the electrode diameter.
- The tip of the electrode is ground flat to minimise the risk of it breaking off when the arc is initiated or during welding (shown below).
- If the vertex angle is increased, the penetration increases.
- If the vertex angle is decreased, bead width increases.
- For AC welding, pure or zirconiated tungsten electrodes are used.
- These are used with a hemispherical (balled) end (as shown below).
- In order to produce a 'balled' end the electrode is ground, an arc initiated and the current increased until it melts the tip of the electrode.



2.6 Shielding gases

The following inert gases can be used as shielding gases for TIG welding:

- Argon
- Helium
- Mixtures of argon and helium

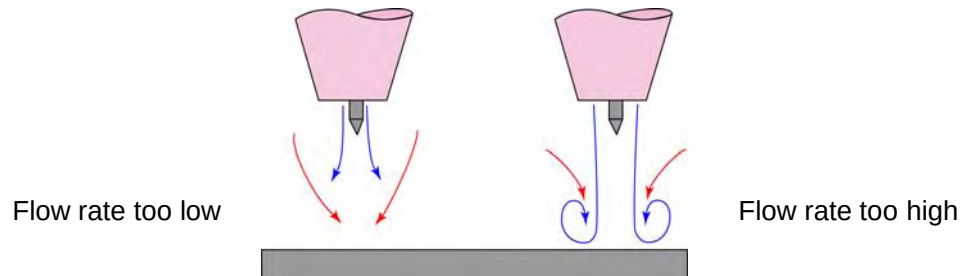
Note: For austenitic stainless steels and some cupro-nickel alloys, argon with up to ~5% hydrogen may be used to improve penetration and reduce porosity

Argon	Performance item	Helium
Lower than with helium, which can be helpful when welding thin sections. Less change in arc voltage with variations in arc length.	Arc voltage	Higher than with argon. Arc is hotter which is helpful in welding thick sections and viscous metals (eg nickel).
Lower than with helium, which gives reduced penetration.	Heating power of the arc	High, which can be of advantage when welding metals with high thermal conductivity and thick materials.
Argon is heavier than air, so requires less gas to shield in the flat and horizontal positions. Also, better draught resistance.	Protection of weld	Helium is lighter than air and requires more gas to properly shield the weld. Exception: overhead welding.
Obtained from the atmosphere by the separation of liquefied air – lower cost and greater availability.	Availability and cost	Obtained by separation from natural gas – lower availability and higher cost.

Characteristics of argon and helium shielding gases for TIG welding

2.6.1 Shielding gas flow rate

- If the gas flow rate is too-low, the shielding gas cannot remove the air from the weld area and this may result in porosity and contamination.
- If the gas flow rate is too high, turbulence occurs at the base of the shielding gas column. Air tends to be sucked in from the surrounding atmosphere and this may also lead to porosity and contamination.
- Shielding gas flow rates are typically in the range ~10 to ~12 l/min



2.6.2 Back purging

It is necessary to protect the back of the weld from excessive oxidation during TIG welding and this is achieved by the use of a purge gas – usually pure argon.

For pipe welding, it is relatively easy to purge the pipe bore, but for plate/sheet welding it is necessary to use a purge channel or sometimes another operator position and move a back purge nozzle as the weld progresses.

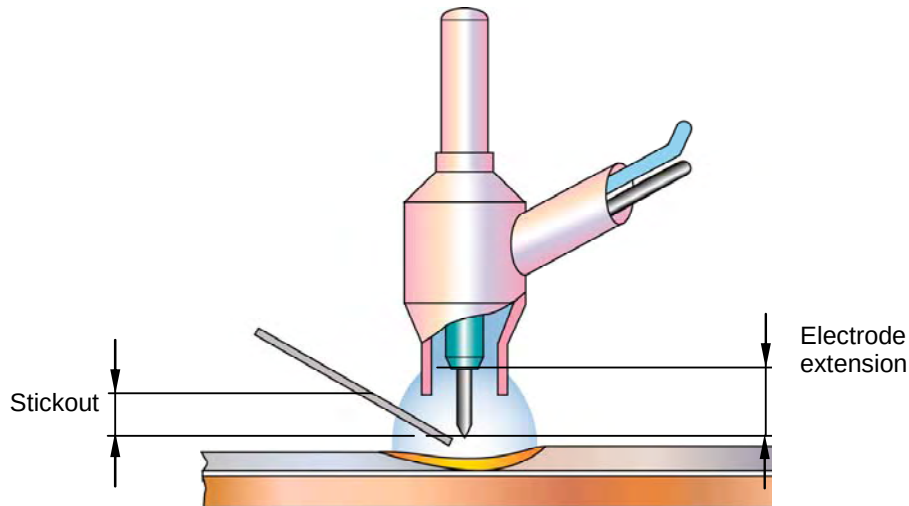
The initial stage of back purging is to exclude all the air at the back of the weld and having allowed sufficient time for this the flow rate should be reduced prior to starting to weld such that there is positive flow (typically ~4 l/min).

Back purging should continue until two or more layers of weld have been deposited.

For C and C-Mn steels it is possible to make satisfactory welds without a back purge.

2.7 Electrode extension

- Electrode extension is the distance from the contact tube to the tungsten tip
- Because the contact tube is recessed inside the gas nozzle, this parameter can be checked indirectly by measuring the stickout length – as shown below



- If the electrode extension is too short, the electrode tip will not be adequately heated leading to an unstable arc
- If the electrode extension is too long, the electrode tip might overheat, cause melting and lead to tungsten inclusions
- As a general rule, stickout length should be 2 to 3 times the electrode diameter

3 Filler Wires

It is usual practice to use filler wires that have a similar composition to the parent metal but they may contain small additions of elements that will combine with any oxygen and nitrogen present.

4 Tungsten Inclusions

Small fragments of tungsten that enter a weld will always show up on radiographs because of the relatively high density of this metal and for most applications will not be acceptable.

Thermal shock to the tungsten causing small fragments to enter the weld pool is a common cause of tungsten inclusions and is the reason why modern power sources have a current slope-up device to minimise this risk.

This device allows the current to rise to the set value over a short period and so the tungsten is heated more slowly and gently.

5 Crater Cracking

Crater cracking is one form of solidification cracking and some filler metals can be sensitive to it.

Modern power sources have a current slope-out device so that at the end of a weld when the welder switches off the current it reduces gradually and the weld pool gets smaller and shallower.

This means that the weld pool has a more favourable shape when it finally solidifies and crater cracking can be avoided.

6 Common Applications of the TIG Process

These include autogenous welding of longitudinal seams in thin walled pipes and tubes, in stainless steel and other alloys, on continuous forming mills.

Using filler wires, TIG is used for making high quality joints in heavier gauge pipe and tubing for the chemical, petroleum and power generating industries.

It is also used in the aerospace industry for such items as airframes and rocket motor cases.

7 Advantages of the TIG process

- Produces superior quality welds, with very low levels of diffusible hydrogen so there is less danger of cold cracking.
- Does not give either weld spatter or slag inclusions which makes it particularly suitable for applications that require a high degree of cleanliness (eg pipework for the food and drinks industry, semiconductors manufacturing, etc).
- Can be used with filler metal and on thin sections without filler, it can produce welds at relatively high speed.
- Enables welding variables to be accurately controlled and is particularly good for controlling weld root penetration in all positions of welding.
- Can weld almost all weldable metals, including dissimilar joints, but it is not generally used for those with low melting points such as lead and tin. The method is especially useful in welding the reactive metals with very stable oxides such as aluminium, magnesium, titanium and zirconium.
- The heat source and filler metal additions are controlled independently and thus it is very good for joining thin base metals.

8 Disadvantages of the TIG Process

- Gives low deposition rates compared with other arc welding processes.
- Need for higher dexterity and welder co-ordination than with MIG/MAG or MMA welding.
- Less economical than MMA or MIG/MAG for sections thicker than ~10mm.
- Difficult to fully shield the weld zone in draughty conditions and so may not be suitable for site/field welding
- Tungsten inclusions can occur if the electrode is allowed to contact the weld pool.
- The process does not have any cleaning action and so has low tolerance for contaminants on filler or base metals.

1 The Process

Known in the USA as gas metal arc welding (GMAW), the MIG/MAG welding process is a versatile technique suitable for both thin sheet and thick section components in most metallic materials. An arc is struck between the end of a wire electrode and the workpiece, melting both to form a weld pool and the wire serves as the source of heat (via the arc at the wire tip) and filler metal for the joint. The wire is fed through a copper contact tube (also called a contact tip) which conducts welding current into the wire. The weld pool is protected from the surrounding atmosphere by a shielding gas fed through a nozzle surrounding the wire. Shielding gas selection depends on the material being welded and the application. The wire is fed from a reel by a motor drive and the welder or machine moves the welding gun or torch along the joint line. The process offers high productivity and is economical because the consumable wire is continuously fed. The process is shown in Figure 1.

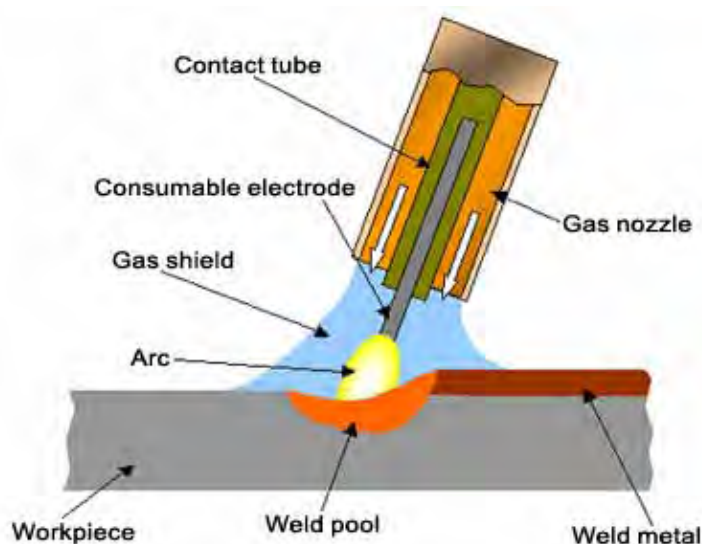


Figure 1 MIG/MAG welding.

The MIG/MAG process uses semi-automatic, mechanised or automatic equipment. In semi-automatic welding, the wire feed rate and arc length are controlled automatically, but the travel speed and wire position are under manual control. In mechanised welding, all parameters are under automatic control, but they can be varied manually during welding, eg steering of the welding head and adjustment of wire feed speed and arc voltage. With automatic equipment, there is no manual intervention during welding. Figure 2 shows equipment required for the MIG/MAG process.

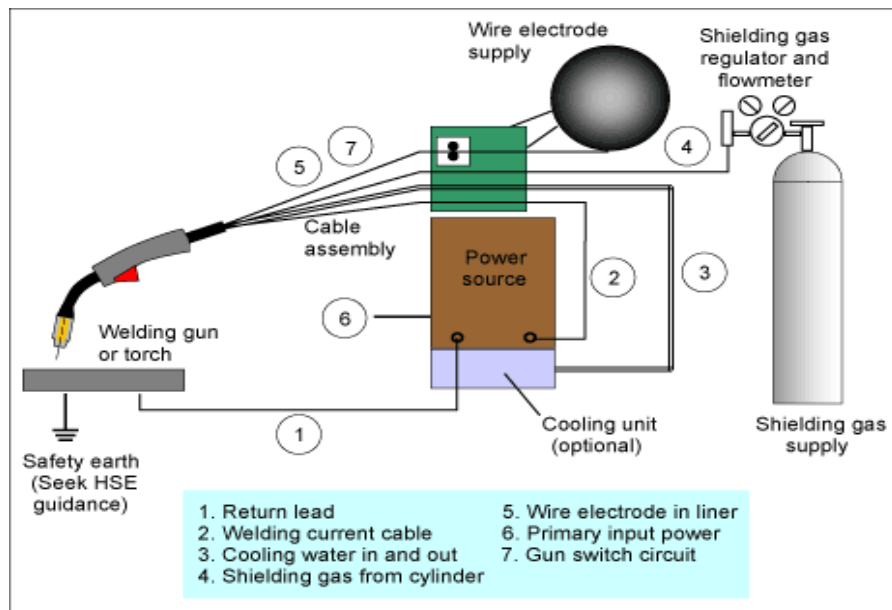


Figure 2 MIG/MAG welding equipment.

Advantages of the MIG/MAG process:

- Continuous wire feed
- Automatic self-regulation of the arc length
- High deposition rate and minimal number of stop/start locations
- High consumable efficiency
- Heat inputs in the range 0.1-2.0kJ/mm
- Low hydrogen potential process
- Welder has good visibility of weld pool and joint line
- Little or no post-weld cleaning
- Can be used in all positions (dip transfer)
- Good process control possibilities
- Wide range of application

Disadvantages:

- No independent control of filler addition
- Difficult to set up optimum parameters to minimise spatter levels
- Risk of lack of fusion when using dip transfer on thicker weldments
- High level of equipment maintenance
- Lower heat input can lead to high hardness values
- Higher equipment cost than MMA welding
- Site welding requires special precautions to exclude draughts which may disturb the gas shield
- Joint and part access is not as good as MMA or TIG welding
- Cleanliness of base metal - slag processes tolerate greater contamination

2 Process Variables

The primary variables in MIG/MAG welding are:

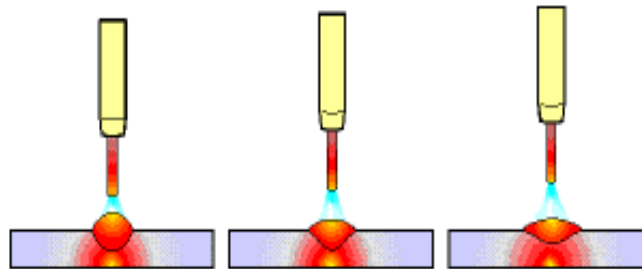
- Welding current/wire feed speed
- Voltage
- Gases
- Travel speed and electrode orientation
- Inductance
- Contact tip to work distance
- Nozzle to work distance
- Shielding gas nozzle
- Type of metal transfer

2.1 Wire feed speed

Increasing the wire feed speed automatically increases the current in the wire. Wires are generally produced in 0.6, 0.8, 1.0, 1.2, 1.4 and 1.6mm diameter.

2.2 Voltage

The voltage setting is the most important setting in spray transfer as it controls the arc length. In dip transfer it also affects the rise of current and the overall heat input into the weld. An increase of both wire feed speed/ current and voltage will increase heat input. The welding connections need to be checked for soundness, as any loose connections will result in resistance and will cause the voltage to drop in the circuit and will affect the characteristic of the welding arc. The voltage will affect the type of transfer achievable, but this is also highly dependent on the type of gas being used.



- Increasing arc voltage
- Reduced penetration, increased width
- Excessive voltage can cause porosity, spatter and undercut

Figure 3 The effect of arc voltage.

2.3 Gases

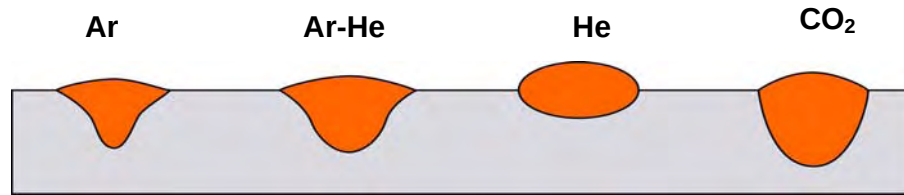


Figure 4 Gas composition effect on weld bead profile.

For non-ferrous metals and their alloys (such as Al, Ni and Cu) an inert shielding gas must be used. This is usually either pure argon or an argon rich gas with a helium addition. The use of a fully inert gas is why the process is also called metal inert gas (MIG) welding and for precise use of terminology this name should only be used when referring to the welding of non-ferrous metals.

The addition of some helium to argon gives a more uniform heat concentration within the arc plasma and this affects the shape of the weld bead profile. Argon-helium mixtures effectively give a hotter arc and so they are beneficial for welding thicker base materials, those with higher, thermal conductivity eg copper or aluminium.

For welding of steels – all grades, including stainless steels – there needs to be a controlled addition of oxygen or carbon dioxide (CO_2) to generate a stable arc and give good droplet wetting. Because these additions react with the molten metal they are referred to as active gases and hence the name metal active gas (MAG) welding is the technical term used when referring to the welding of steels.

100% CO_2

CO_2 gas cannot sustain spray transfer as the ionisation potential of the gas is too high. Because of this high ionisation potential it gives very good penetration, but promotes globular droplet, transfer also a very unstable arc and lots of spatter.

Argon +15 to 20% CO_2

The percentage of CO_2 or oxygen depends on the type of steel being welded and the mode of metal transfer being used. Argon has a much lower ionisation potential and can sustain spray transfer above 24 welding volts. Argon gives a very stable arc and little spatter, but lower penetration than CO_2 . Both argon and CO_2 gas in mixtures of between 5-20% CO_2 in argon to get the benefit of both gases ie good penetration with a stable arc and gives very little spatter. CO_2 gas is much cheaper than argon or its mixtures and is widely used for carbon and some low alloy steels.

Argon +1 to 5%CO₂

Widely used for stainless steels and some low alloy steels.

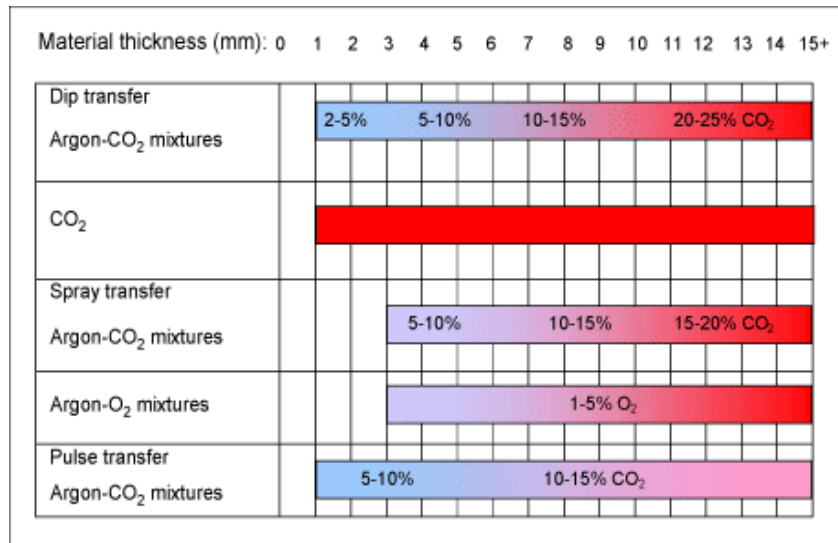


Figure 5 Active shielding gas mixtures for MAG welding of carbon, carbon-manganese and low alloy steels
(Blue is a cooler gas mixture; red is a hotter mixture.)

Gas mixtures - helium in place of argon gives a hotter arc, more fluid weld pool and better weld profile. These quaternary mixtures permit higher welding speeds, but may not be suitable for thin sections.

Stainless steels

Austenitic stainless steels are typically welded with argon-CO₂/O₂ mixtures for spray transfer or argon-helium-CO₂ mixtures for all modes of transfer. The oxidising potential of the mixtures are kept to a minimum (2-2.5% maximum CO₂ content) to stabilise the arc, but with minimum effect on corrosion performance. Because austenitic steels have a high thermal conductivity, the addition of helium helps to avoid lack of fusion defects and overcome the high heat dissipation into the material. Helium additions are up to 85%, compared with ~25% for mixtures used for carbon and low alloy steels. CO₂-containing mixtures are sometimes avoided to eliminate potential carbon pick-up.

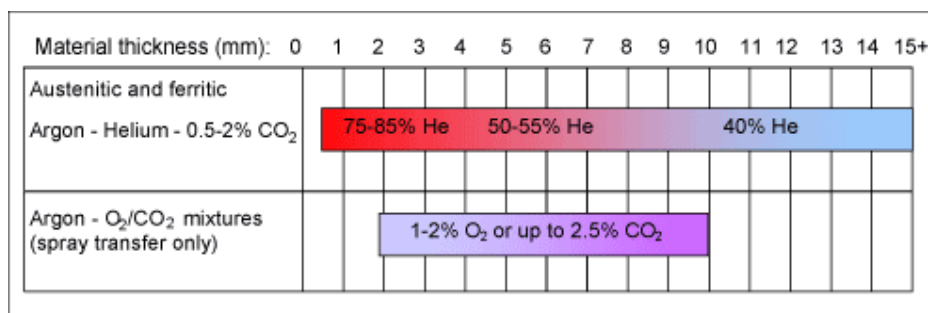


Figure 6 Active shielding gas mixtures for MAG welding of stainless steels.
(Blue is a cooler gas mixture; red is a hotter mixture.)

For martensitic and duplex stainless steels, specialist advice should be sought. Some Ar-He mixtures containing up to 2.5%N₂ are available for welding duplex stainless steels.

Light alloys (aluminium magnesium, titanium, copper and nickel and their alloys)

Inert gases are used for light alloys and those that are sensitive to oxidation. Welding grade inert gases should be purchased rather than commercial purity to ensure good weld quality.

Argon

Argon can be used for aluminium because there is sufficient surface oxide available to stabilise the arc. For materials that are sensitive to oxygen, such as titanium and nickel alloys, arc stability may be difficult to achieve with inert gases in some applications. The density of argon is approximately 1.4 times that of air. Therefore, in the downhand position, the relatively heavy argon is very effective at displacing air. A disadvantage is that when working in confined spaces, there is a risk of argon building up to dangerous levels and asphyxiating the welder.

Argon-helium mixtures

Argon is most commonly used for MIG welding of light alloys, but some advantage can be gained by the use of helium and argon/helium mixtures. Helium possesses a higher thermal conductivity than argon. The hotter weld pool produces improved penetration and/or an increase in welding speed. High helium contents give a deep broad penetration profile, but produce high spatter levels. With less than 80% argon, a true spray transfer is not possible. With globular-type transfer, the welder should use a 'buried' arc to minimise spatter. Arc stability can be problematic in helium and argon-helium mixtures, since helium raises the arc voltage and therefore there is a larger change in arc voltage with respect to arc length. Helium mixtures require higher flow rates than argon shielding in order to provide the same gas protection.

There is a reduced risk of lack of fusion defects when using argon-helium mixtures, particularly on thick section aluminium. Ar-He gas mixtures will offset the high heat dissipation in material over about 3mm thickness.

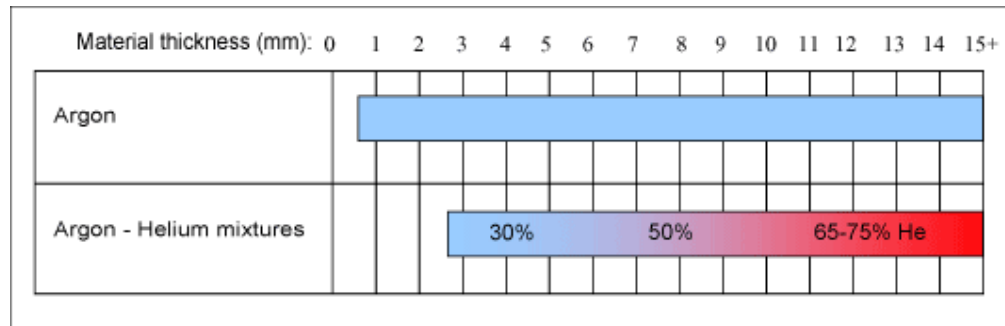


Figure 7 Inert shielding gas mixtures for MIG welding of aluminium, magnesium, titanium, nickel and copper alloys.

(Blue is a cooler gas mixture; red is a hotter mixture.)

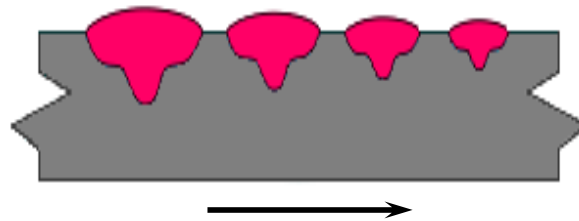
A summary table of shielding gases and mixtures used for different base materials is given in *below*.

Summary of shielding gas mixtures for MIG/MAG welding

Metal	Shielding gas	Reaction behaviour	Characteristics
Carbon steel	Argon-CO ₂	Slightly oxidising	Increasing CO ₂ content gives hotter arc, improved arc stability, deeper penetration, transition from finger-type to bowl-shaped penetration profile, more fluid weld pool giving flatter weld bead with good wetting, increased spatter levels, better toughness than CO ₂ . Minimum 80% argon for axial spray transfer. General-purpose mixture: Argon-10-15%CO ₂ .
	Argon-O ₂	Slightly oxidising	Stiffer arc than Ar-CO ₂ mixtures, minimises undercutting, suited to spray transfer mode, lower penetration than Ar-CO ₂ mixtures, finger-type weld bead penetration at high current levels. General-purpose mixture: Argon-3% CO ₂ .
	Ar-He-CO ₂	Slightly oxidising	Substitution of helium for argon gives hotter arc, higher arc voltage, more fluid weld pool, flatter bead profile, more bowl-shaped and deeper penetration profile and higher welding speeds, compared with Ar-CO ₂ mixtures. High cost.
	CO ₂	Oxidising	Arc voltages 2-3V higher than Ar-CO ₂ mixtures, best penetration, higher welding speeds, dip transfer or buried arc technique only, narrow working range, high spatter levels, low cost.
Stainless steels	He-Ar-CO ₂	Slightly oxidising	Good arc stability with minimum effect on corrosion resistance (carbon pick-up), higher helium contents designed for dip transfer, lower helium contents designed for pulse and spray transfer. General-purpose gas: He-Ar-2%CO ₂ .
	Argon-O ₂	Slightly oxidising	Spray transfer only, minimises undercutting on heavier sections, good bead profile.
Aluminium, copper, nickel, titanium alloys	Argon	Inert	Good arc stability, low spatter, and general-purpose gas. Titanium alloys require inert gas backing and trailing shields to prevent air contamination.
	Argon-helium	Inert	Higher heat input offsets high heat dissipation on thick sections, lower risk of lack of fusion defects, higher spatter, higher cost than argon.

2.4 Travel speed and electrode orientation

The faster the travel speed the less penetration, narrower bead width and the higher risk of undercut



- Increasing travel speed
- Reduced penetration and width, undercut

Figure 8 The effect of travel speed

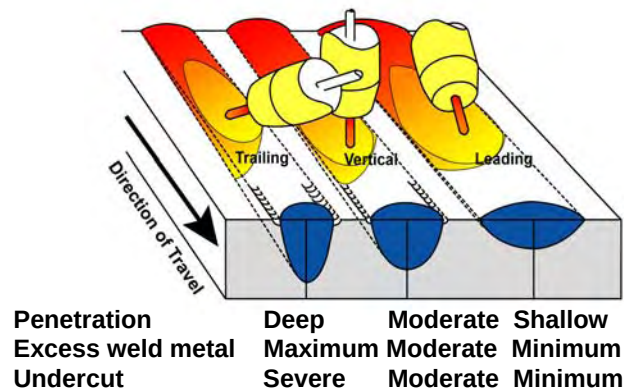


Figure 9 The effect of torch angle

2.5 Effect of contact tip to workpiece distance (CTWD)

The CTWD has an influence over the welding current because of resistive heating in the electrode extension (see Figure 10). The welding current required to melt the electrode at the required rate (to match the wire feed speed) reduces as the CTWD is increased. Long electrode extensions can cause lack of penetration, for example, in narrow gap joints or with poor manipulation of the welding gun. Conversely, the welding current increases when the CTWD is reduced. This provides the experienced welder with a means of controlling the current during welding, but can result in variable penetration in manual welding with a constant voltage power source.

As the electrode extension is increased, the burn-off rate increases for a given welding current due to increased resistive heating. Increasing the electrode extension, eg in mechanised applications, is therefore one method of increasing deposition rates, as the wire feed speed is increased to maintain the required welding current.

Resistive heating depends on the resistivity of the electrode, length of the electrode extension and wire diameter. The effect is therefore more pronounced for welding materials which have high resistivity, such as steels. The electrode extension should be kept small when small diameter wires are being used to prevent excessive heating in the wire and avoid the resulting poor bead shape.

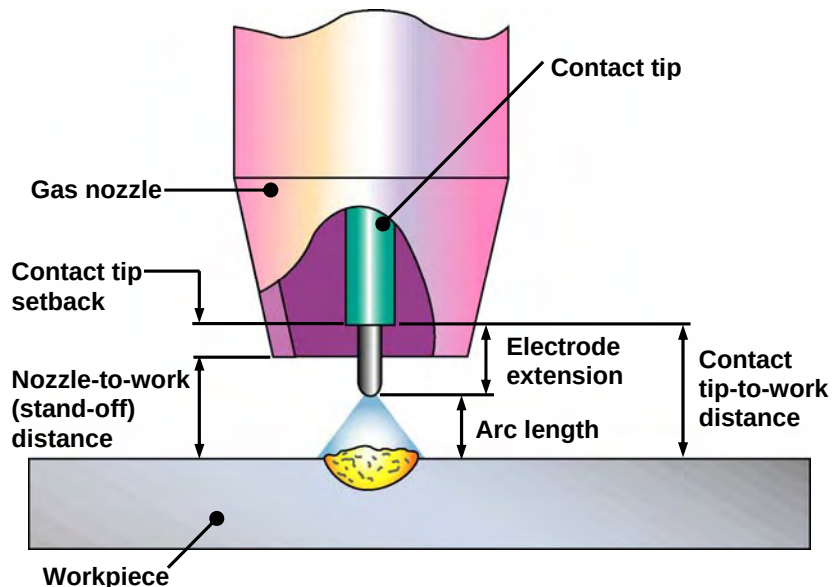


Figure 10 Contact tip to workpiece distance; electrode extension; and nozzle to workpiece distance

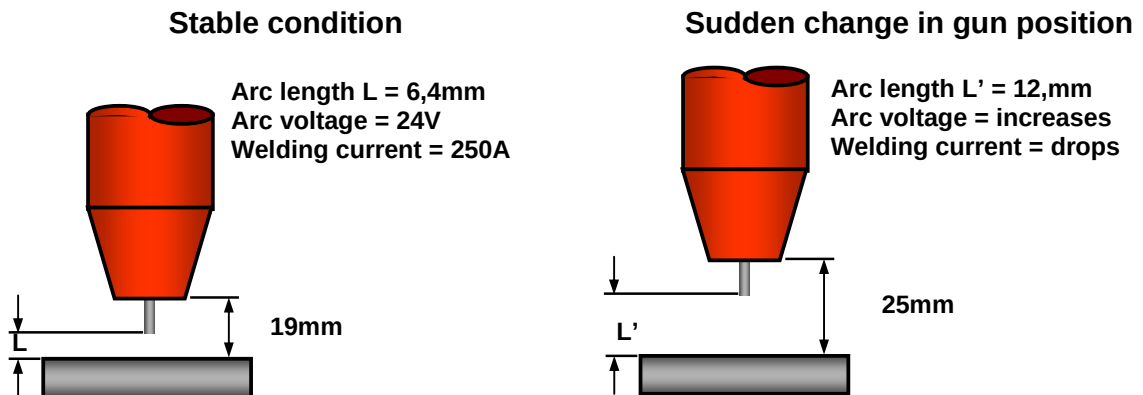


Figure 11 The effect of increasing the contact tip to workpiece distance

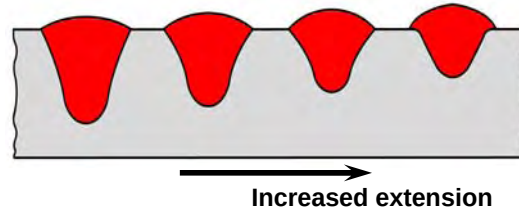


Figure 12 The effect of increasing electrode extension

At short CTWDs, radiated heat from the weld pool can cause overheating of the contact tube and welding torch. This can lead to spatter adherence and increased wear of the contact tube.

The electrode extension should be checked when setting-up welding conditions or when fitting a new contact tube. Normally measured from the contact tube to the workpiece (Figure 13), suggested CTWDs for the principal metal transfer modes are:

Metal transfer mode	CWTD, mm
Dip	10-15
Spray	20-25
Pulse	15-20

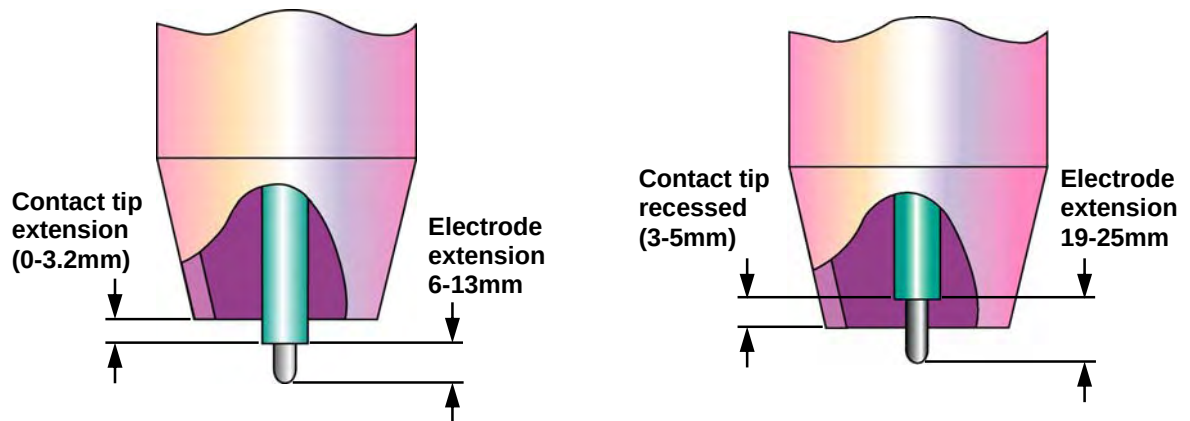


Figure 13 Suggested contact tip to work distance

2.6 Effect of nozzle to work distance

Nozzle to work distance (see Figure 13) has a considerable effect on gas shielding efficiency; a decrease having the effect of stiffening the column. The nozzle to work distance is typically 12-15mm. If the CTWD is simultaneously reduced, however, the deposition rate at a given current is decreased and visibility and accessibility are affected; so, in practice, a compromise is necessary. The following gives suggested settings for the mode of metal transfer being used.

Metal transfer mode	Contact tip position relative to nozzle
Dip	2mm inside to 2mm protruding
Spray	4-8mm inside
Spray (aluminium)	6-10mm inside

2.7 Shielding gas nozzle

The purpose of the shielding gas nozzle is to produce a laminar gas flow to protect the weld pool from atmospheric contamination. Nozzle sizes range from 13 to 22mm diameter. The nozzle diameter should be increased in relation to the size of the weld pool. Therefore, larger diameter nozzles are used for high current, spray transfer application, and smaller diameter nozzles for dip transfer. The flow rate must also be tuned to the nozzle diameter and shielding gas type to give sufficient weld pool coverage. Gas nozzles for dip transfer welding tend to be tapered at the outlet of the nozzle.

Joint access and type should also be considered when selecting the required gas nozzle and flow rate. Use of too small a nozzle may cause it to become obstructed by spatter more quickly and, if the wire bends on leaving the contact tube, the shielding envelope and arc location may not coincide.

2.8 Types of metal transfer

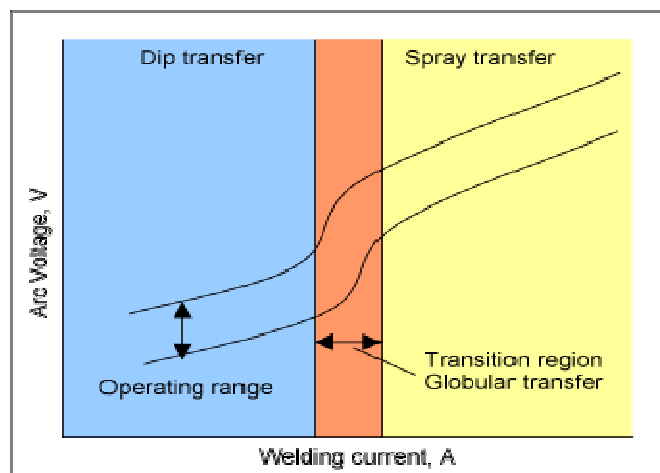


Figure 14 Arc characteristic curve.

Dip transfer

Key characteristics:

- Metal transfer by wire dipping or short-circuiting into the weld pool
- Relatively low heat input process
- Low weld pool fluidity
- Used for thin sheet metal above 0.8mm and typically less than 3.2mm, positional welding of thicker section and root runs in open butt joints
- Process stability and spatter can be a problem if poorly tuned
- Lack of fusion risk if poorly set up and applied
- Not used for non-ferrous metals and alloys

In dip transfer the wire short-circuits the arc between 50-200 times/second. This type of transfer is normally achieved with CO₂ or mixtures of CO₂ and argon gas + low amps and welding volts <24V.



Figure 15 Dip transfer.

Spray transfer

Key characteristics

- Free-flight metal transfer
- High heat input
- High deposition rate
- Smooth, stable arc
- Used on steels above 6mm thickness and aluminium alloys above 3mm thickness

Spray transfer occurs at high currents and voltages. Above the transition current, metal transfer is of a fine spray of small droplets, which is projected across the arc with low spatter levels. The high welding current produces strong electromagnetic forces (known as the pinch effect) that cause the molten filament supporting the droplet to neck down. The droplets detach from the tip of the wire and accelerate across the arc gap. The frequency at which the droplets detach increases with increasing current. The droplet size equates to the wire diameter at the threshold level but decreases significantly as the welding current increases. At very high currents (wire feed speeds), the molten droplets can start to rotate (rotating transfer). The arc current is flowing for the entire period of the drop detachment, resulting in maximum penetration and a high heat input. When the correct arc voltage to give spray transfer is used, the arc is short, with the wire tip 1-3mm from the surface of the plate.

With steels it can be used only in downhand butts and H/V fillet welds, but gives higher deposition rate, penetration and fusion than dip transfer because of the continuous arc heating. It is mainly used for steel plate thicknesses >3mm but has limited use for positional welding due to the potential large weld pool involved.

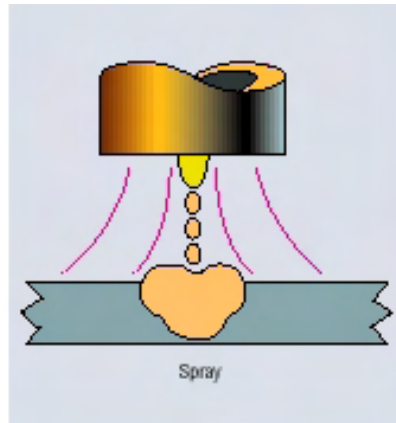


Figure 16 Spray transfer.

Pulsed transfer

Key characteristics

- Free-flight droplet transfer without short-circuiting over the entire working range
- Very low spatter
- Lower heat input than spray transfer
- Reduced risk of lack of fusion compared with dip transfer
- Control of weld bead profile for dynamically loaded parts
- Process control/flexibility
- Enables use of larger diameter, less expensive wires with thinner plates – more easily fed (a particular advantage for aluminium welding)

Pulsing the welding current extends the range of spray transfer operation well below the natural transition from dip to spray transfer. This allows smooth, spatter-free spray transfer at mean currents below the transition level, eg 50-150A and at lower heat inputs. Pulsing was introduced originally for control of metal transfer by imposing artificial cyclic operation on the arc system by applying alternately high and low currents.

A typical pulse waveform and the main pulse welding variables are shown in *Figure 17*. A low background current (typically 20-80A) is supplied to maintain the arc, keep the wire tip molten, give stable anode and cathode roots and maintain average current during the cycle. Droplet detachment occurs during a high current pulse at current levels above the transition current level. The pulse of current generates very high electromagnetic forces, which cause a strong pinch effect on the metal filament supporting the droplet; the droplet is detached and is projected across the arc gap. Pulse current and current density must be sufficiently high to ensure that spray transfer (not globular) always occurs so that positional welding can be used.

Pulse transfer uses pulses of current to fire a single globule of metal across the arc gap at a frequency of 50-300 pulses/second. Pulse transfer is a development of spray transfer, that gives positional welding capability for steels, combined with controlled heat input, good fusion and high productivity. It may be used for all sheet steel thickness >1mm, but is mainly used for positional welding of steels >6mm.

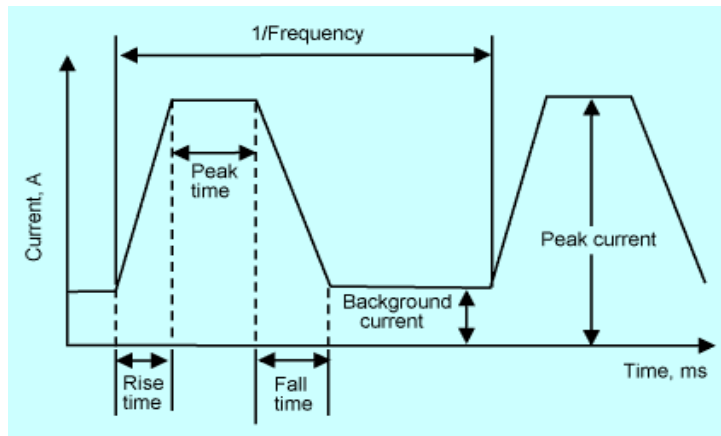


Figure 17 Pulsed welding waveform and parameters

Globular transfer

Key characteristics

- Irregular metal transfer
- Medium heat input
- Medium deposition rate
- Risk of spatter
- Not widely used in the UK; can be used for mechanised welding of medium thickness steels (typically 3-6mm) in the flat (PA) position

The globular transfer range occupies the transitional range of arc voltage between free-flight and fully short-circuiting transfer. Irregular droplet transfer and arc instability are inherent, particularly when operating near the transition threshold. In globular transfer, a molten droplet of several times the electrode diameter forms on the wire tip. Gravity eventually detaches the globule when its weight overcomes surface tension forces, and transfer takes place often with excessive spatter. Before transfer occurs, the arc wanders and its cone covers a large area, dissipating energy.

There is a short duration short-circuit when the droplet contacts with the molten pool, but rather than causing droplet transfer, it occurs as a result of it. Although the short-circuit is of very short duration, some inductance is necessary to reduce spatter, although to the operator the short-circuits are not discernible and the arc has the appearance of a free-flight type.

To further minimise spatter levels, it is common to operate with a very short arc length, and in some cases a buried arc technique is adopted. Globular transfer can only be used in the flat position and is often associated with lack of penetration, fusion defects and uneven weld beads, because of the irregular transfer and tendency for arc wander.

2.9 Inductance

What does inductance do?

When MIG/MAG welding in the dip transfer mode, the welding electrode touches the weld pool, causing a short-circuit. During the short-circuit, the arc voltage is nearly zero. If the constant voltage power supply responded instantly, very high current would immediately begin to flow through the welding circuit. The rapid rise in current to a high value would melt the short-circuited electrode free with explosive force, dispelling the weld metal and causing considerable spatter.

Inductance is the property in an electrical circuit that slows down the rate of current rise (Figure 18). The current travelling through an inductance coil creates a magnetic field. This magnetic field creates a current in the welding circuit that is in opposition to the welding current. Increasing the inductance will also increase the arc time and decrease the frequency of short-circuiting.

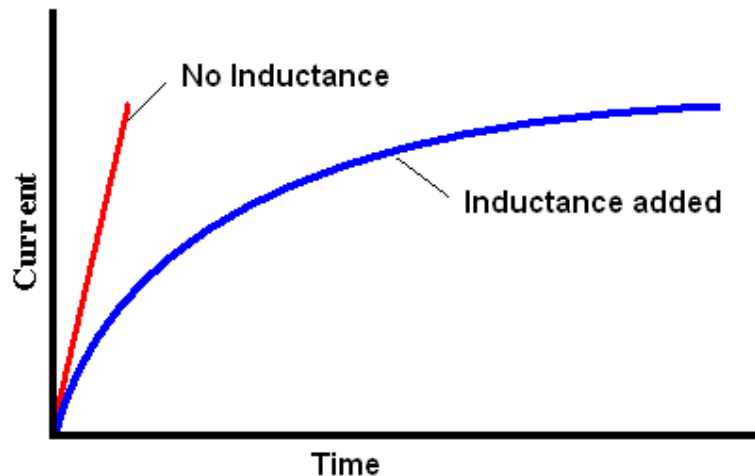


Figure 18 Relationship between inductance and current rise.

For each electrode feed rate, there is an optimum value of inductance. Too little inductance results in excessive spatter, if too much, the current will not rise fast enough and the molten tip of the electrode is not heated sufficiently causing the electrode to stub into the base metal. Modern electronic power sources automatically set the inductance to give a smooth arc and metal transfer.

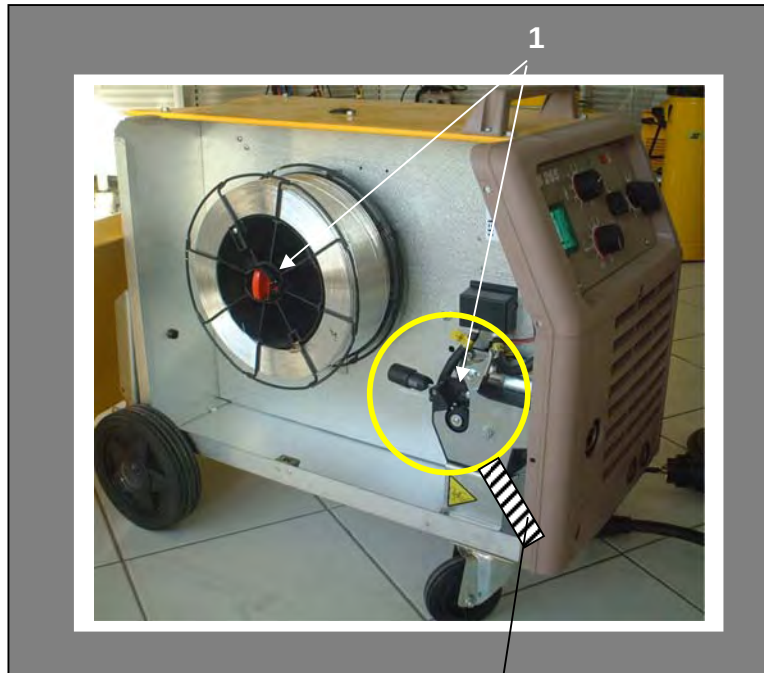
3 Metal Inert Gas Welding - Basic Equipment Requirements



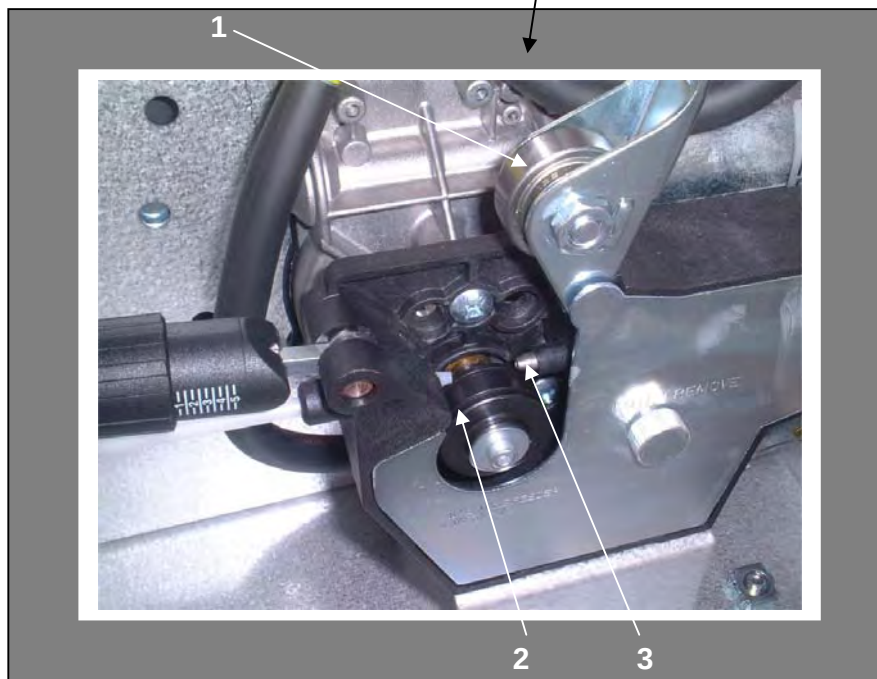
- 1) Power source-transformer/rectifier (constant voltage type)
- 2) Inverter power source
- 3) Power hose assembly (liner, power cable, water hose, gas hose)
- 4) Liner
- 5) Spare contact tips
- 6) Torch head assembly
- 7) Power-return cable and clamp
- 8) 15kg wire spool (copper coated and uncoated wires)
- 9) Power control panel
- 10) External wire feed unit

The MIG/MAG wire drive assembly

1) An internal wire drive system



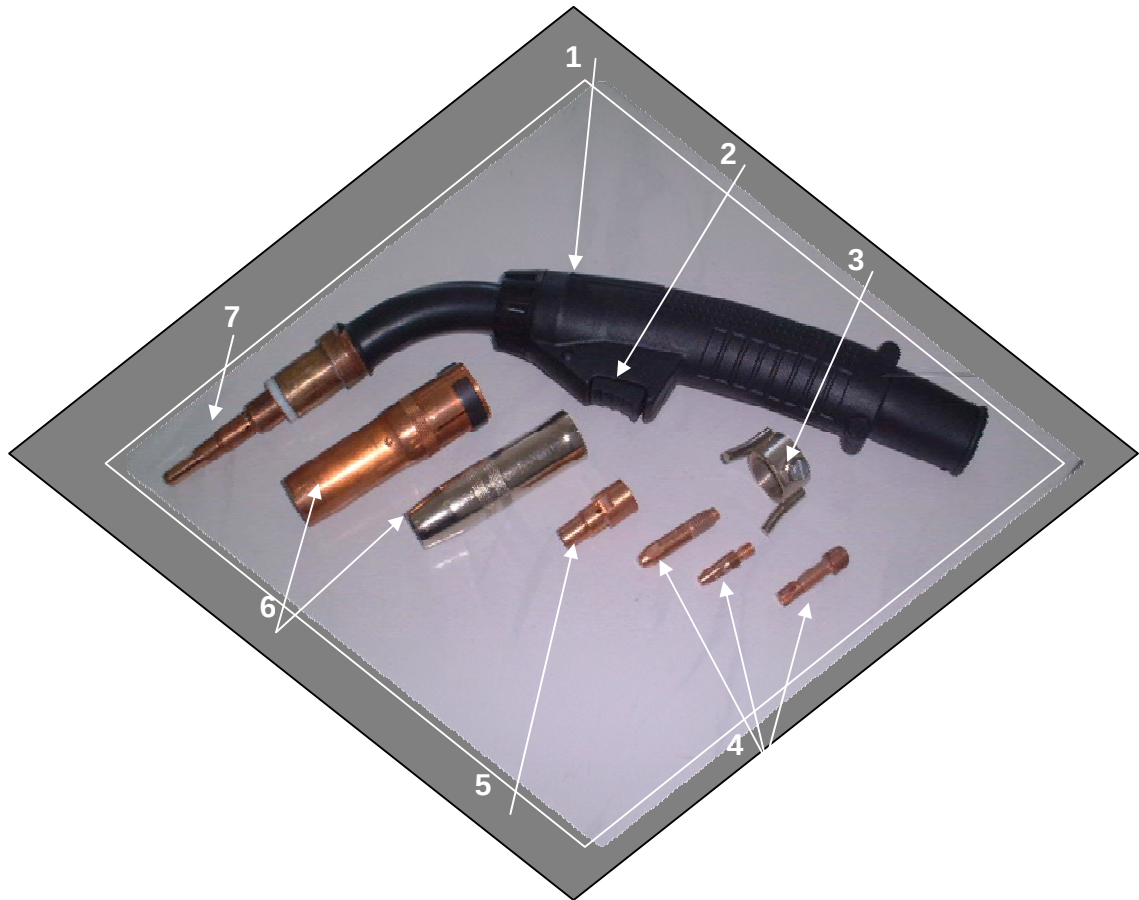
1) Flat plain top drive roller



2) Half groove bottom drive roller

3) Wire guide

The MIG torch head assembly



- 1) Torch body
- 2) On/off or latching switch
- 3) Spot welding spacer attachment
- 4) Contact tips
- 5) Gas diffuser
- 6) Spare shrouds
- 7) Torch head assembly (minus the shroud)

4 Important Inspection Points/Checks When MIG/MAG Welding

4.1 Welding equipment

A visual check should be made to ensure the welding equipment is in good condition.

4.2 Electrode wire

The diameter, specification and quality of wire are the main inspection headings. The level of de-oxidation of the wire is an important factor with single, double and triple de-oxidised wires being available.

The higher the level of de-oxidants in the wire, the lower the chance of occurrence of porosity in the weld. The quality of the wire winding, copper coating and temper are also important factors in minimising wire feed problems.

Quality of wire windings and increasing costs

→
a) Random wound. b) Layer wound. c) Precision layer wound.

4.3 Drive rolls and liner

Check the drive rolls are the correct size for the wire and that the pressure is only hand tight, or just sufficient to drive the wire. Any excess pressure will deform the wire to an ovular shape, making the wire very difficult to drive through the liner, resulting in arcing in the contact tip and excessive wear of the contact tip and liner.

Check that the liner is the correct type and size for the wire. A size of liner will generally fit 2 sizes of wire ie 0.6 and 0.8, 1.0 and 1.2, 1.4 and 1.6mm diameter. Steel liners are used for steel wires and Teflon liners for aluminium wires.

4.4 Contact tip

Check that the contact tip is the correct size for the wire being driven and check the amount of wear frequently. Any loss of contact between the wire and contact tip will reduce the efficiency of current pick. Most steel wires are copper coated to maximise the transfer of current by contact between two copper surfaces at the contact tip but this also inhibits corrosion. The contact tip should be replaced regularly.

4.5 Connections

The length of the electric arc in MIG/MAG welding is controlled by the voltage settings, achieved by using a constant voltage volt/amp characteristic inside the equipment. Any poor connection in the welding circuit will affect the nature and stability of the electric arc and is thus a major inspection point.

4.6 Gas and gas flow rate

The type of gas used is extremely important to MIG/MAG welding, as is the flow rate from the cylinder, which must be adequate to give good coverage over the solidifying and molten metal to avoid oxidation and porosity.

4.7 Other variable welding parameters

Checks should be made for correct wire feed speed, voltage, speed of travel, and all other essential variables of the process given on the approved welding procedure.

4.8 Safety checks

Checks should be made on the current carrying capacity or duty cycle of equipment and electrical insulation. Correct extraction systems should be in use to avoid exposure to ozone and fumes.

A check should always be made to ensure that the welder is qualified to weld the procedure being employed.

Typical welding imperfections:

- **Silica inclusions** (on ferritic steels only) caused by poor inter-run cleaning
- **Lack of sidewall fusion** during dip transfer welding thick section vertically down
- **Porosity** caused by loss of gas shield and low tolerance to contaminants
- **Burn through** from using the incorrect metal transfer mode on sheet metal.

5 Flux Cored Arc Welding (FCAW)

In the mid-1980s the development of self- and gas-shielded FCAW was a major step in the successful application of on-site semi-automatic welding, and has also enabled a much wider range of materials to be welded.

The cored wire consists of a metal sheath containing a granular flux. This flux can contain elements that would normally be used in MMA electrodes so the process has a very wide range of applications.

In addition, gas producing elements and compounds can be added to the flux so the process can be independent of a separate gas shield, which restricts the use of conventional MIG/MAG welding in many field applications.

Most wires are sealed mechanically and hermetically with various forms of joint. The effectiveness of the joint of the wire is an inspection point of cored wire welding as moisture can easily be absorbed into a damaged or poor seam.

Wire types commonly used are:

- **Rutile** which give good positional capabilities.
- **Basic** also positional but good on 'dirty' material
- **Metal cored** higher productivity, some having excellent root run capabilities.
- **Self-shielded** no external gas needed.

Baking of cored wires is ineffective and will not restore the condition of a contaminated flux within a wire.

Note that unlike MMA electrodes the potential hydrogen levels and mechanical properties of welds with rutile wires can equal those of the basic types.

6 Summary of Solid Wire MIG/MAG GMAW

Equipment requirements

- Transformer/rectifier (constant voltage type).
- Power and power return cable.
- Inert, active or mixed shielding gas (argon or CO₂).
- Gas hose, flow meter, and gas regulator.
- MIG torch with hose, liner, diffuser, contact tip and nozzle.
- Wire feed unit with correct drive rolls.
- Electrode wire to correct specification and diameter.
- Correct visor/glass, all safety clothing and good extraction.

Parameters and inspection points

- Wire feed speed/amperage.
- Open circuit and welding voltage.
- Wire type and diameter.
- Gas type and flow rate.
- Contact tip size and condition.
- Roller type, size and pressure.
- Liner size.
- Inductance settings.
- Insulation/extraction.
- Connections (voltage drops).
- Travel speed, direction and angles.

Typical welding imperfections

Silica inclusions.

Lack of fusion (dip transfer).

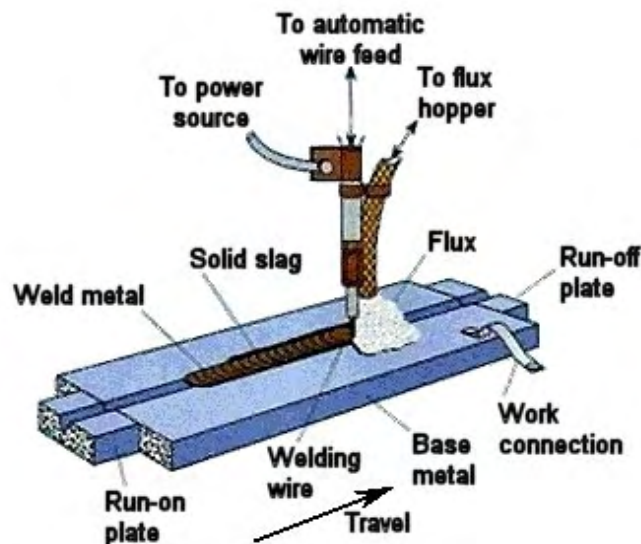
Surface porosity.

Advantages and disadvantages

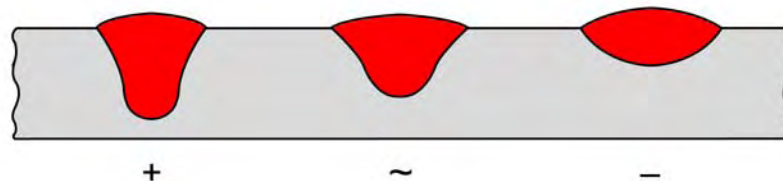
Advantages	Disadvantages
High productivity	Lack of fusion (dip transfer)
Easily automated	Small range of consumables
All positional (dip, pulse and FCAW)	Protection for site working
Material thickness range	Complex equipment
Continuous electrode	High ozone levels

1 The Process

Submerged arc welding (**SAW**), is a welding process where an arc is struck between a continuous bare wire and the parent plate. The arc, electrode end and molten pool are submerged in an agglomerated or fused powdered flux, which turns into a gas and slag in its lower layers when subjected to the heat of the arc, thus protecting the weld from contamination. The wire electrode is fed continuously by a feed unit of motor driven rollers, which are usually voltage-controlled to ensure an arc of constant length. The flux is fed from a hopper fixed to the welding head, and a tube from the hopper spreads the flux in a continuous elongated mound in front of the arc along the line of the intended weld and of sufficient depth to submerge the arc completely so there is no spatter, the weld is shielded from the atmosphere and there are no ultra-violet or infra-red radiation effects (see below). Unmelted flux is reclaimed for use. The use of powdered flux restricts the process to the flat and horizontal-vertical welding positions.



Submerged arc welding is noted for its ability to employ high weld currents owing to the properties and functions of the flux. Such currents give deep penetration and high deposition rates. Generally a DC electrode positive polarity is employed up to about 1000A because it produces deep penetration. On some applications (ie cladding operations) DC electrode negative is needed to reduce penetration and dilution. At higher currents or in the case of multiple electrode systems, AC is often preferred to avoid the problem of arc blow (when used with multiple electrode systems, DC electrode positive is used for the lead arc and AC is used for the trail arc).



Difficulties sometimes arise in ensuring conformity of the weld with a pre-determined line owing to the obscuring effect of the flux. Where possible, a guide wheel to run in the joint preparation is positioned in front of the welding head and flux hoppers.

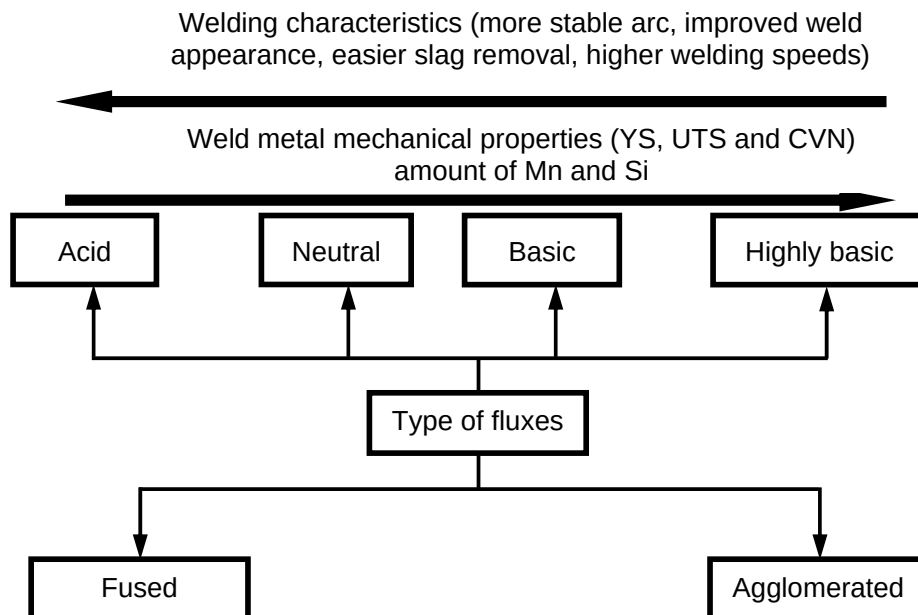
Submerged arc welding is widely used in the fabrication of ships, pressure vessels, linepipe, railway carriages and anywhere where long welds are required. It can be used to weld thicknesses from 1.5mm upwards.

Materials joined

- Welding of carbon steels.
- Welding low alloy steels (eg fine grained and creep resisting).
- Welding stainless steels.
- Welding nickel alloys.
- Cladding to base metals to improve wear and corrosion resistance.

2 Fluxes

Flux may be defined as granular mineral compounds mixed to various formulations.



The fused fluxes are produced when the constituents are dry mixed and melted in an electric furnace and thereafter granulated by pouring the molten mixture into water or on to an ice block. Subsequently, these particles are crushed and screened to yield a uniform glass-like product.

Advantages of fused fluxes

- Good chemical homogeneity.
- Less hygroscopic, thus handling and storage are easier.
- Allow fines (fine powders) to be removed without changes in composition.
- They can easily be recycled through the system without significant change in particle size or composition.

Disadvantages of fused fluxes

- Limitations in composition as some components, such as basic carbonates would be unable to withstand the melting process.
- Difficult to add deoxidisers and ferro-alloys (due to segregation or extremely high loss).

In case of agglomerated fluxes constituents may be bonded by mixing the dry constituents with potassium or sodium silicate. This wet mixture is then pelletised, dried, crushed and screened to size.

Advantages of agglomerated fluxes

- Deoxidisers and alloying elements can easily be added to the flux to adjust the weld metal composition.
- Allow a thicker flux layer when welding.
- Can be identified by colour coding.

Disadvantages of agglomerated fluxes

- Are generally more hygroscopic (re-baking hardly practical).
- Gas may be evolved from the slag as it is melted, leading to porosity.
- There may be changes in weld metal chemical composition from the segregation of fine particles produced by the mechanical handling of the granulated flux.

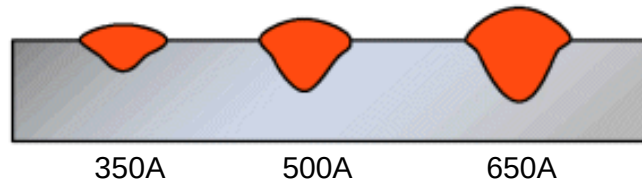
3 Process Variables

There are several variables which when changed can have an effect on the weld appearance and mechanical properties:

- Welding current.
- Type of flux and particle distribution.
- Arc voltage.
- Travel speed.
- Electrode size.
- Electrode extension.
- Type of electrode.
- Width and depth of the layer of flux.
- Electrode angle (leading, trailing).
- Polarity.
- Single, double or multi wire-system.

3.1 Welding current

- Increasing current increases penetration and wire melt-off rate

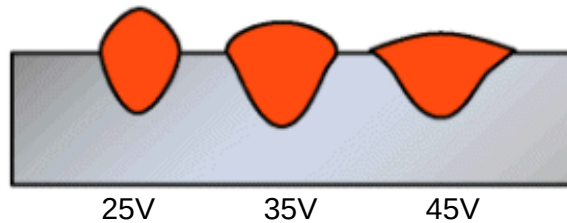


Welding current effect on weld profile (2.4mm electrode diameter, 35V arc voltage and 61cm/min travel speed)

- Excessively high current produces a deep penetrating arc with a tendency to burn-through, undercut or a high, narrow bead prone to solidification cracking.
- Excessively low current produces an unstable arc, lack of penetration and possibly a lack of fusion.

3.2 Arc voltage

Arc voltage adjustment varies the length of the arc between the electrode and the molten weld metal. If the arc voltage increases, the arc length increases and vice versa. The voltage principally determines the shape of the weld bead cross section and its external appearance.



*Arc voltage effect on weld profile (2.4mm electrode diameter,
500A welding current and 61cm/min travel speed)*

Increasing the arc voltage with constant current and travel speed will:

- Produce a flatter and wider bead
- Increase flux consumption
- Tend to reduce porosity caused by rust or scale on steel
- Help to bridge excessive root opening when fit-up is poor
- Increase pick-up of alloying elements from the flux when they are present

Excessively high arc voltage will:

- Produce a wide bead shape that is subject to solidification cracking
- Make slag removal difficult in groove welds
- Produce a concave shaped fillet weld that may be subject to cracking
- Increase undercut along the edge(s) of fillet welds
- Over alloy the weld metal, via the flux

Reducing the arc voltage with constant current and travel speed will:

- Produce a stiffer arc which improves penetration in a deep weld groove and resists arc blow

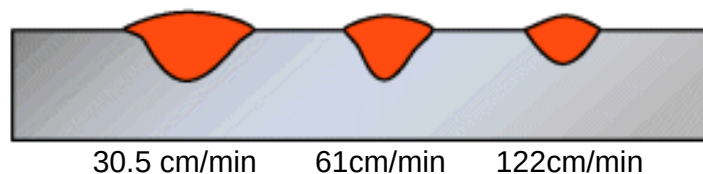
Excessively low arc voltage will:

- Produce a high, narrow bead
- Cause difficult slag removal along the weld toes

3.3 Travel speed

If the travel speed is increased:

- Heat input per unit length of weld is decreased
- Less filler metal is applied per unit length of weld and consequently less excess weld metal
- Penetration decreases and thus the weld bead becomes smaller

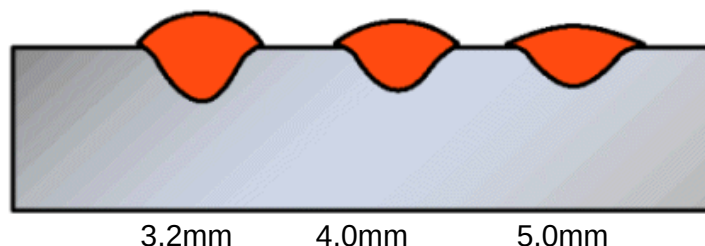


Travel speed effect on weld profile (2.4mm electrode diameter, 500A welding current and 35V arc voltage)

3.4 Electrode size

Electrode size affects:

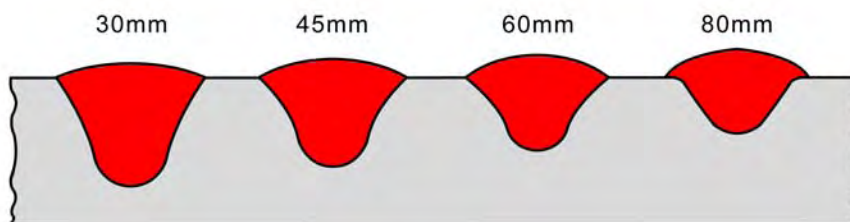
- Weld bead shape and depth of penetration at a given current: A high current density results in a stiff arc that penetrates into the base metal. Conversely, a lower current density in the same size electrode results in a soft arc that is less penetrating.
- Deposition rate: At any given amperage setting, a small diameter electrode will have a higher current density and deposition rate of molten metal than a larger diameter electrode. However, a larger diameter electrode can carry more current than a smaller one, so the larger electrode can ultimately produce a higher deposition rate at higher amperage.



Electrode size effect on weld profile (600A welding current, 30V arc voltage and 76cm/min travel speed)

3.5 Electrode extension

The electrode extension is the distance the continuous electrode protrudes beyond the contact tip. At high current densities, resistance heating of the electrode between the contact tip and the arc can be utilised to increase the electrode melting rate (as much as 25-50%). The longer the extension, the greater the amount of heating and the higher the melting rate (see below).



3.6 Type of electrode

An electrode with a low electrical conductivity, such as stainless steel, can with a normal electrode extension, experience greater resistance heating. Thus for the same size electrode and current, the melting rate of a stainless steel electrode will be higher than that of a carbon steel electrode.

3.7 Width and depth of flux

The width and depth of the layer of granular flux influence the appearance and soundness of the finished weld as well as the welding action. If the granular layer is too deep, the arc is too confined and a rough weld with a rope-like appearance is likely to result, it may also produce local flat areas on the surface often referred to as gas flats. The gases generated during welding cannot readily escape and the surface of the molten weld metal is irregularly distorted. If the granular layer is too shallow, the arc will not be entirely submerged in flux. Flashing and spattering will occur. The weld will have a poor appearance and may show porosity.

4 Storage and Care of Consumables

Care must be given to fluxes supplied for SAW which, although they may be dry when packaged, may be exposed to high humidity during storage. In such cases they should be dried in accordance with the manufacturer's recommendations before use, or porosity or cracking may result.

Ferrous wire coils supplied as continuous feeding electrodes are usually copper-coated. This provides some corrosion resistance, ensures good electrical contacts and helps in smooth feeding. Rust and mechanical damage should be avoided in such products, as they interrupt smooth feeding of the electrode. Rust will be detrimental to weld quality generally since it is a hygroscopic (may contain or absorb moisture) material and thus can lead to hydrogen induced cracking.

Contamination by carbon containing materials such as oil, grease, paint and drawing lubricants is especially harmful with ferrous metals. Carbon pick-up in the weld metal can cause a marked and usually undesirable change in properties. Such contaminants may also result in hydrogen being absorbed in the weld pool.

Welders should always follow the manufacturer's recommendations for consumables storage and handling.

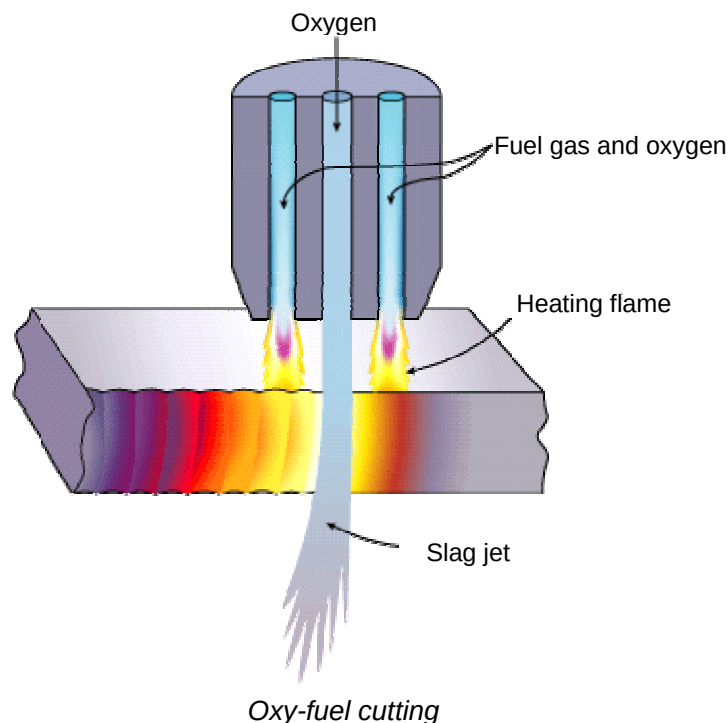
5 Power Sources

In arc welding it is principally the current which determines the amount of heat generated and this controls the melting of the electrode and parent metal and also such factors as penetration, and bead shape and size. Voltage and arc length are also important factors with increasing voltage leading to increasing arc length and vice-versa. Usually in SAW a constant voltage (or flat) characteristic power source is used.

Power can be supplied from a welding generator with a flat characteristic or a transformer/rectifier arranged to give output voltages of approximately 14-50V and ranges of current according to the output of the unit these can be in excess of 1000A.

1 Oxy-Fuel Cutting

The oxy-fuel cutting process cuts or removes metal by the chemical reaction of oxygen with the metal at elevated temperatures. The necessary temperature is provided by a gas flame, which preheats and brings the material up to the burning temperature (approximately 850°C). Once this temperature is achieved, a stream of oxygen is released, which rapidly oxidises most of the metal and performs the actual cutting operation. Metal oxides, together with molten metal, are expelled from the cut by the kinetic energy of the oxygen stream. Moving the torch across the workpiece produces a continuous cutting action.



In order to be cut by the oxy-fuel cutting process, a material must simultaneously fulfil two conditions:

- Burning temperature must be below the parent material melting point.
- Melting temperature of the oxides formed during the cutting process must be below the parent material melting point.

These two conditions are fulfilled by carbon steels and some low alloy steels. However, the oxides of many of the alloying elements in steels, such as aluminium and chromium have melting points higher than those of iron oxides. These high melting point oxides (which are refractory in nature!) may shield the material in the kerf so that fresh iron is not continuously exposed to the cutting oxygen stream, leading to a decrease of the cutting speed and ultimately an unstable process. In practice, the process is

effectively limited to low alloy steels containing <0.25%C, <5%Cr, <5%Mo, <5%Mn and <9%Ni.

Advantages of oxy-fuel cutting

- Steels can generally be cut faster than by most machining methods.
- Section shapes and thicknesses difficult to produce by mechanical means can be cut economically by oxy-fuel cutting.
- Basic equipment costs are low compared to machine tools.
- Manual equipment is very portable and can be used on site.
- Cutting direction can be changed rapidly on a small radius.
- Large plates can be cut rapidly in place by moving the torch rather than the plate.
- Economical method of plate edge preparation.

Disadvantages of oxy-fuel cutting

- Dimensional tolerances are significantly poorer than machine tool capabilities.
- Process is essentially limited to cutting carbon and low alloy steels.
- Preheat flame and expelled red hot slag present fire and burn hazards to plant and personnel.
- Fuel combustion and oxidation of the metal require proper fume control and adequate ventilation.
- Hardenable steels may require pre- and/or post-heat adjacent to the cut edges to control their metallurgical structures and mechanical properties.
- Special process modifications are needed for cutting high alloy steels and cast irons (ie iron powder or flux addition).
- Being a thermal process, expansion and shrinkage of the components during and after cutting must be taken into consideration.

1.1 Requirements for gases

Oxygen used for cutting operations should have a purity of 99.5% or higher. Lower purity will result in a decrease in cutting speed and an increase in consumption of cutting oxygen thus reducing the efficiency of the operation. With oxygen purity below 95% cutting becomes a melt-and-wash action that is usually unacceptable.

The preheating flame has the following functions in the cutting operation:

- Raises the temperature of the steel to the ignition point.
- Adds heat energy to the work to maintain the cutting reaction.
- Provides a protective shield between the cutting oxygen stream and the atmosphere.
- Dislodges from the upper surface of the steel any rust, scale, paint or other foreign substance that would stop or retard the normal forward progress of the cutting action.

Factors to be considered when selecting a fuel gas include:

- Time required for preheating when starting cuts.
- Effect on cutting speed and productivity.
- Cost and availability.
- Volume of oxygen required per volume of fuel gas to obtain a neutral flame.
- Safety in transporting and handling.

Some of the more common fuel gases used are acetylene, natural gas (methane), propane, propylene and methylacetylene propadiene (MAPP) gas.

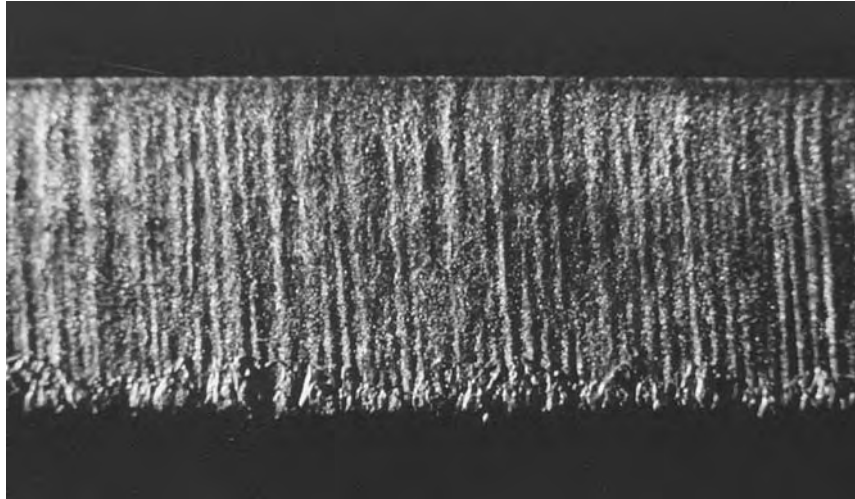
Fuel gas characteristics and their applications

Fuel gas	Main characteristics	Applications
Acetylene	Highly focused, high temperature flame Rapid preheating and piercing Low oxygen requirement	Cutting of thin plates Bevel cuts Short, multi-pierce cuts
Propane	Low temperature flame, high heat content Slow preheating and piercing High oxygen requirement	Cutting of thicker sections (100-300mm), long cuts
MAPP	Medium temperature flame	Cutting underwater
Propylene	Medium temperature flame	Cutting of thicker sections
Methane	Low temperature flame	Cutting of thicker sections

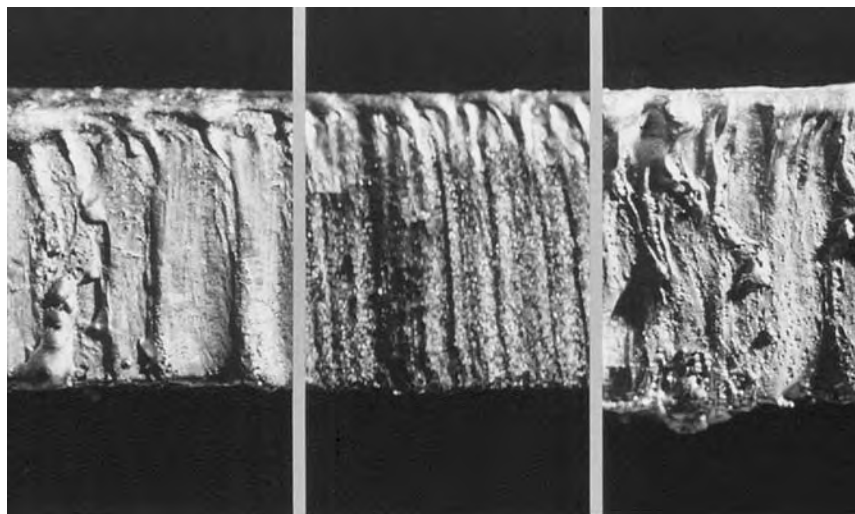
1.2 Oxy-fuel gas cutting quality

Generally, oxy-fuel cuts are characterised by:

- Large kerf (<2mm)
- Low roughness values ($R_a < 50\mu\text{m}$)
- Poor edge squareness ($>0.7\text{mm}$)
- Wide HAZ ($>1\text{mm}$)



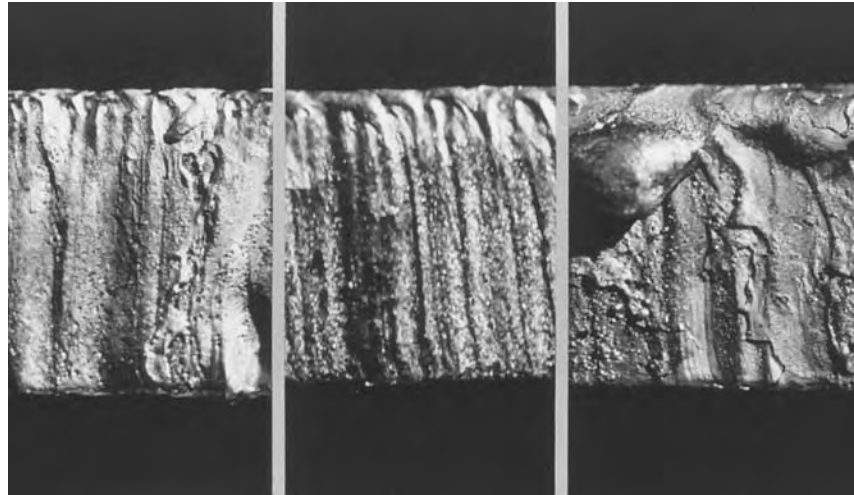
The face of a satisfactory cut has a sharp top edge, drag lines, which are fine and even, little oxide and a sharp bottom edge. Underside is free of slag.



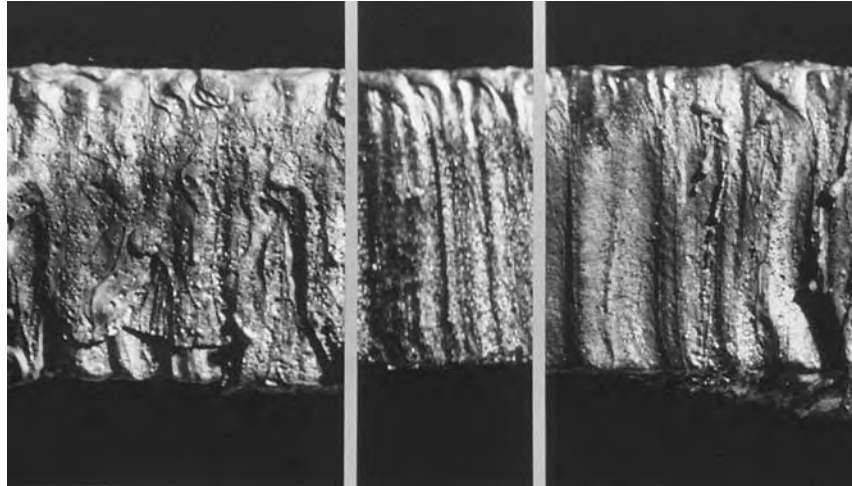
A satisfactory cut is shown in the centre. If the cut is too slow (left) the top edge is melted and there are deep grooves in the lower portion of the face. Scaling is heavy and the bottom edge may be rough, with adherent dross. If the cut is too fast (right) the appearance is similar, with an irregular cut edge. Plate thickness 12mm.



In the case of a very fast travel speed, the drag lines are coarse and at an angle to the surface with an excessive amount of slag sticking to the bottom edge of the plate, due to the oxygen jet trailing with insufficient oxygen reaching the bottom of the cut.



A satisfactory cut is again shown in the centre. If the preheating flame is too low (left) the most noticeable effect on the cut edge is deep gouges in the lower part of the cut face. If the preheating flame is too high (right) the top edge is melted, the cut is irregular and there is an excess of adherent dross. Plate thickness 12mm.



As before, a satisfactory cut is shown in the centre. If the blowpipe nozzle is too high above the work (left) excessive melting of the top edge occurs with much oxide. If the torch travel speed is irregular (right) uneven spacing of the drag lines can be observed together with an irregular bottom surface and adherent oxide. Plate thickness 12mm.

2 Plasma Arc Cutting

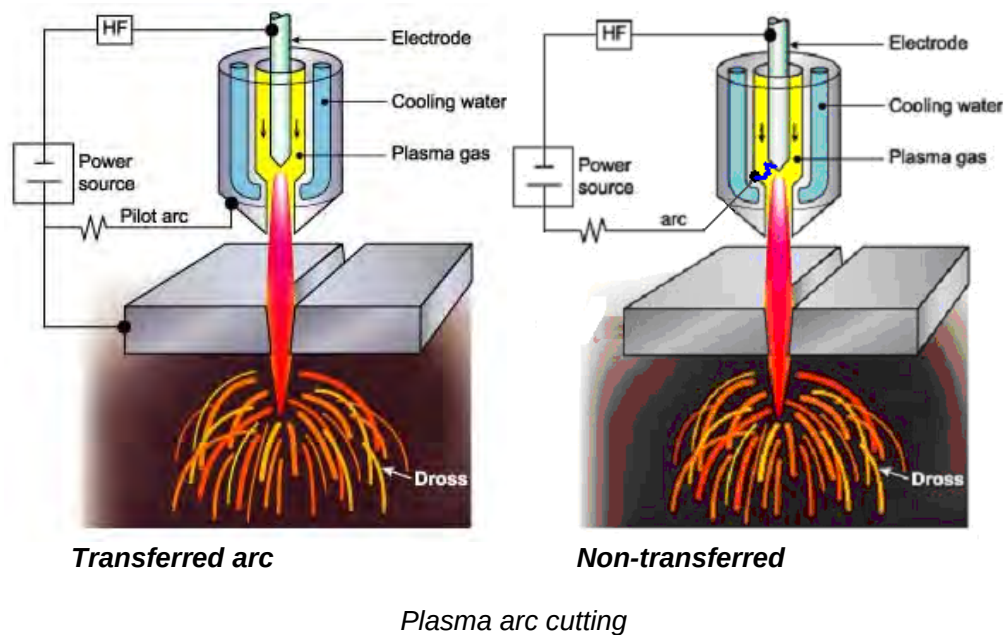
Plasma arc cutting is an arc cutting process that uses a constricted arc, which removes the molten metal with a high velocity jet of ionised gas issuing from the constricting orifice. First, a pilot arc is struck between a tungsten electrode and a water-cooled nozzle. The arc is then transferred to the workpiece, thus being constricted by the orifice downstream of the electrode. As plasma gas passes through this arc, it is heated rapidly to a high temperature, expands and is accelerated as it passes through the constricting orifice towards the workpiece. The orifice directs the super heated plasma stream from the electrode toward the workpiece. When the arc melts the workpiece, the high velocity jet blows away the molten metal. The cutting arc attaches or transfers to the workpiece. This is known as the transferred arc method. However, where materials are non-electrical conductors there is a method known as non-transferred arc where the positive and negative poles are housed inside the torch body creating the arc and the plasma jet stream travels toward the workpiece.

Advantages of plasma arc cutting

- Not only limited to materials which are electrical conductors; as a consequence, is widely used for cutting all types of stainless steels, non-ferrous materials and non-electrical conductive materials
- Operates at a much higher energy level compared to oxy-fuel cutting resulting in faster cutting speed
- Instant start-up is particularly advantageous for interrupted cutting; this also allows cutting without preheat

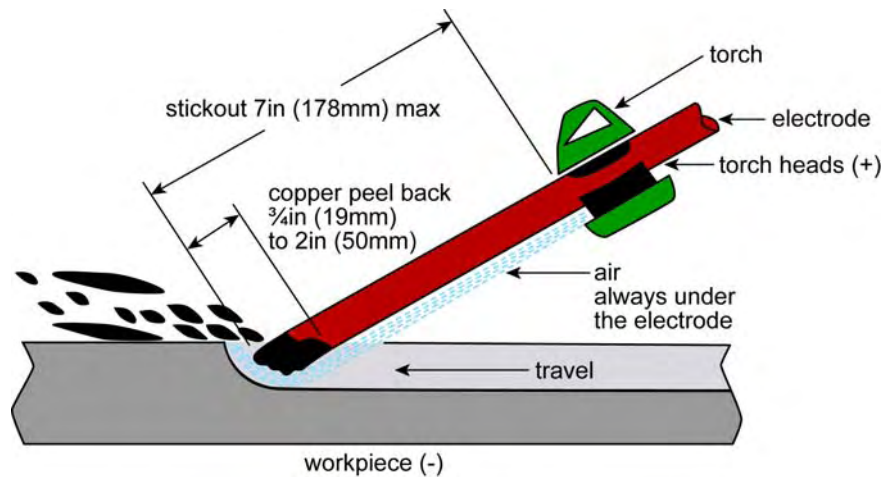
Disadvantages of plasma arc cutting

- Dimensional tolerances are significantly poorer than machine tool capabilities.
- The process introduces hazards such as fire, electric shock (due to the high OCV), intense light, fumes, gases and noise levels that may not be present with other processes. However, in the case of underwater cutting, the level of fumes, UV radiation and noise are reduced to a low level.
- Compared to oxy-fuel cutting, plasma arc cutting equipment tends to be more expensive and requires a fairly large amount of electric power.
- Being a thermal process, expansion and shrinkage of the components during and after cutting must be taken into consideration.
- Cut edges slightly tapered.



3 Arc Air Gouging

During the arc air gouging process, the metal to be gouged or cut is melted with an electric arc and blown away with a high velocity jet of compressed air. A special torch directs the compressed air stream along the electrode and underneath it. The torch is connected to an arc welding machine and any compressed air line, which delivers approximately 690MPa (100psi) of compressed air. Since pressure is not critical, a regulator is not necessary. The electrode is made of graphite and copper-coated to increase the current pick-up and operating life. This process is usually used for gouging and bevelling, being able to produce U and J preparations. It can be applied to both ferrous and non-ferrous materials.



Arc air gouging

Advantages of arc air gouging

- Fast – it is approximately 5 times faster than chipping.
- Easily controllable, removes defects with precision. Defects are clearly visible and may be followed with ease. The depth of cut is easily regulated and slag does not deflect or hamper the cutting action.
- Low equipment cost – no gas cylinders or regulators are necessary except on site.
- Economical to operate – no oxygen or fuel gas required. The welder may also do the gouging (there are no qualification requirements for this operation).
- Easy to operate – the equipment is similar to MMA equipment except the torch and air supply hose.
- Compact – the torch is not much larger than an MMA electrode holder, allowing work in confined areas.
- Versatile.
- Can be automated.

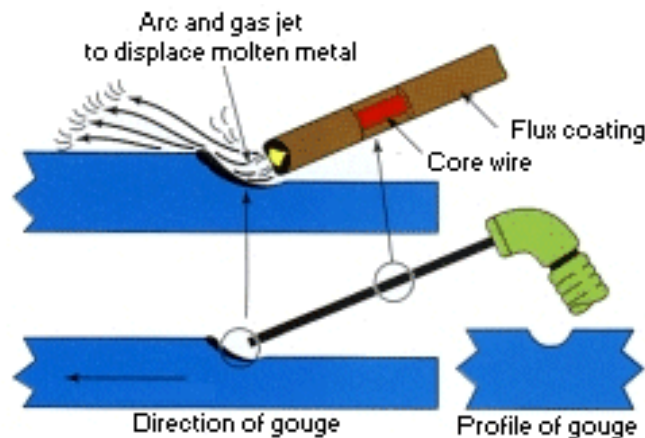
Disadvantages of arc air gouging

- Other cutting processes usually produce a better and quicker cut.
- Requires a large volume of compressed air.
- Increases the carbon content leading to an increase in hardness in the case of cast iron and hardenable metals. In stainless steels it can lead to carbide precipitation and sensitisation. For this reason, grinding of the carbide layer usually follows arc air gouging.
- Introduces hazards such as fire (due to discharge of sparks and molten metal), fumes, noise and intense light.

4 Manual Metal Arc Gouging

The arc is formed between the tip of the electrode and the workpiece. It requires special purpose electrodes with thick flux coatings to generate a strong arc force and gas stream. Unlike MMA welding where a stable weld pool must be maintained, this process forces the molten metal away from the arc zone to leave a clean cut surface.

The gouging process is characterised by the large amount of gas, which is generated to eject the molten metal. However, because the arc/gas stream is not as powerful as a gas or a separate air jet, the surface of the gouge is not as smooth as an oxy-fuel or air carbon arc gouge.



Manual metal arc gouging

Although DCEN is preferred, an AC constant current power source can also be used.

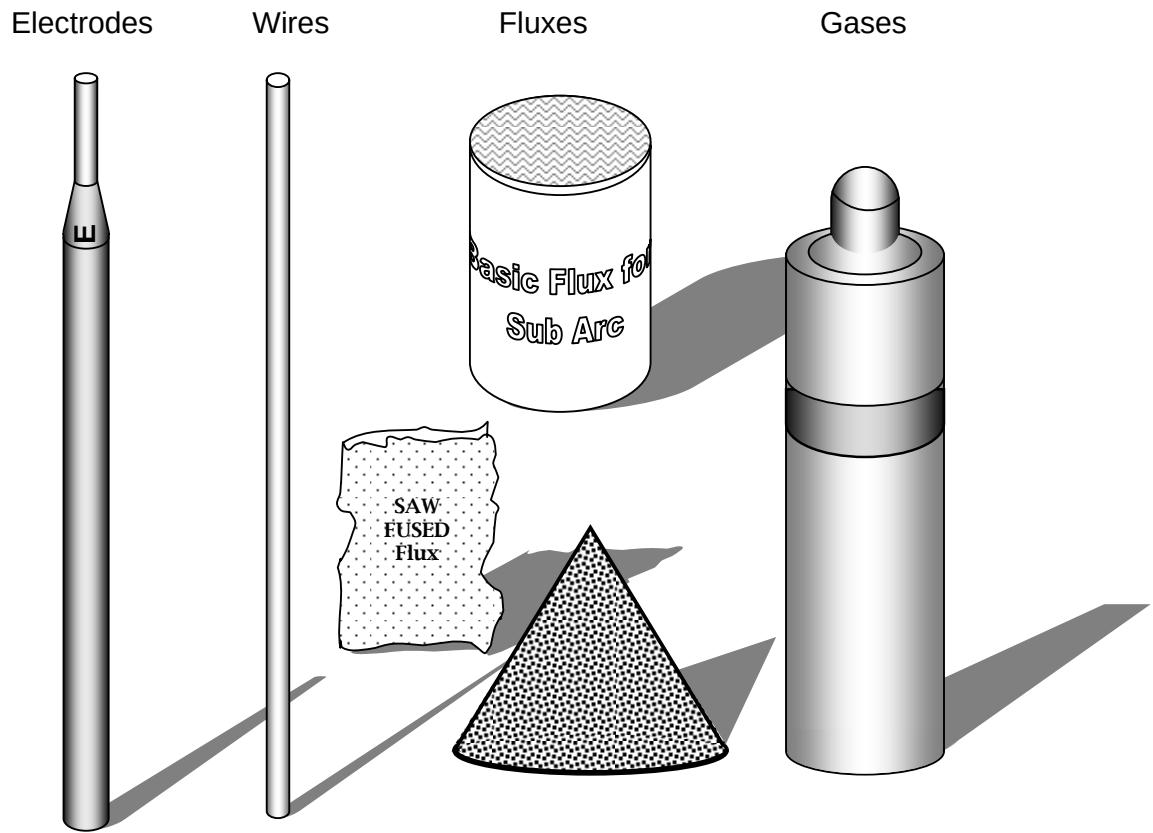
MMA gouging is used for localised gouging operations, removal of defects for example, and where it is more convenient to switch from a welding to a gouging electrode rather than use specialised equipment. Compared with alternative gouging processes, metal removal rates are low and the quality of the gouged surface is inferior.

When correctly applied, MMA gouging can produce relatively clean gouged surfaces. For general applications, welding can be carried out without the need to dress by grinding. However when gouging stainless steel, a thin layer of higher carbon content material will be produced - this should be removed by grinding.

Welding consumables are defined as all that is used up during the production of a weld.

This list could include all things used up in the production of a weld, however, we normally refer to welding consumables as those items used up by a particular welding process.

These are:



When inspecting welding consumables arriving at site it is important that they are inspected for the following:

- Size.
- Type or specification.
- Condition.
- Storage.

The checking of ***suitable storage conditions*** for all consumables is a ***critical*** part of the welding inspector's duties.

1 Consumables for MMA Welding

Welding consumables for MMA consist of a core wire typically between 350 and 450mm length and 2.5-6mm diameter. Other lengths and diameters are available. The wire is covered with an extruded flux coating. The core wire is generally of low quality rimming steel as the weld can be considered as a casting and therefore the weld can be refined by the addition of cleaning or refining agents in the flux coating. The flux coating contains many elements and compounds that all have a variety of jobs during welding. Silicon is mainly added as a de-oxidising agent (in the form of ferro-silicate), which removes oxygen from the weld metal by forming the oxide silica. Manganese additions of up to 1.6% will improve the strength and toughness of steel. Other metallic and non-metallic compounds are added that have many functions, **some** of which are:

- Aid arc ignition.
- Improve arc stabilisation.
- Produce a shielding gas to protect the arc column.
- Refine and clean the solidifying weld metal.
- Form a slag which protects the solidifying weld metal.
- Add alloying elements.
- Control hydrogen content of the weld metal.
- Form a cone at the end of the electrode, which directs the arc.

Electrodes for MMA/SMAW are grouped depending on the main constituent in their flux coating, which in turn has a major effect on the weld properties and ease of use. The common groups are:

Group	Constituent	Shield gas	Uses	AWS A 5.1
Rutile	Titania	Mainly CO ₂	General purpose	E 6013
Basic	Calcium compounds	Mainly CO ₂	High quality	E 7018
Cellulosic	Cellulose	Hydrogen + CO ₂	Pipe root runs	E 6010

Some basic electrodes may be tipped with a carbon compound, which eases arc ignition.





Symbol	Tensile Strength N/mm ²	Yield Strength min. N/mm ²	Elongation min. %
35	440-570	355	22
38	470-600	380	20
42	500-640	420	20
46	530-680	460	20
50	560-720	500	18

Symbol	Welding position
1	All positions
2	All positions, except vertical down
3	Flat butt weld, flat fillet weld, horizontal-vertical fillet weld
4	Flat butt weld, flat fillet weld
5	Vertical down and positions according to symbol 3

Symbol	Metal recovery, %	Type of current
1	< 105	AC + DC
2	< 105	DC
3	> 105 ≤ 125	AC + DC
4	> 105 ≤ 125	DC
5	> 125 ≤ 160	AC + DC
6	> 125 ≤ 160	DC
7	> 160	AC + DC
8	> 160	DC

E 46

3

1Ni

B

5

4

H5

Covered electrode
for manual metal arc
welding.

Symbol	Coating type
A	Acid
B	Basic
C	Cellulosic
R	Rutile
RR	Rutile (thick coated)
RC	Rutile-Cellulosic
RA	Rutile-Acid
RB	Rutile-Basic

Symbol	Hydrogen content, ml/100 g deposited weld metal, max.
H5	5
H10	10
H15	15

Symbol	Impact Energy Charpy-V Temp °C for 47J min.
Z	No requirements
A	+20
0	0
2	-20
3	-30
4	-40
5	-50
6	-60

Symbol	Chemical composition of all-weld metal, % *		
	Mn	Mo	Ni
No symbol	2.0	—	—
Mo	1.4	0.3 - 0.6	—
MnMo	> 1.4 - 2.0	0.3 - 0.6	—
1Ni	1.4	—	0.6 - 1.2
2Ni	1.4	—	1.8 - 2.6
3Ni	1.4	—	> 2.6 - 3.8
Mn1Ni	> 1.4 - 2.0	—	0.6 - 1.2
1NiMo	1.4	0.3 - 0.6	0.6 - 1.2
Z	Any other agreed composition		

* If not specified Mo < 0.2, Ni < 0.3, Cr < 0.2, V < 0.05, Nb < 0.05, Cu < 0.3
Single values shown in the table mean maximum values.

The electrode classification system of EN 499

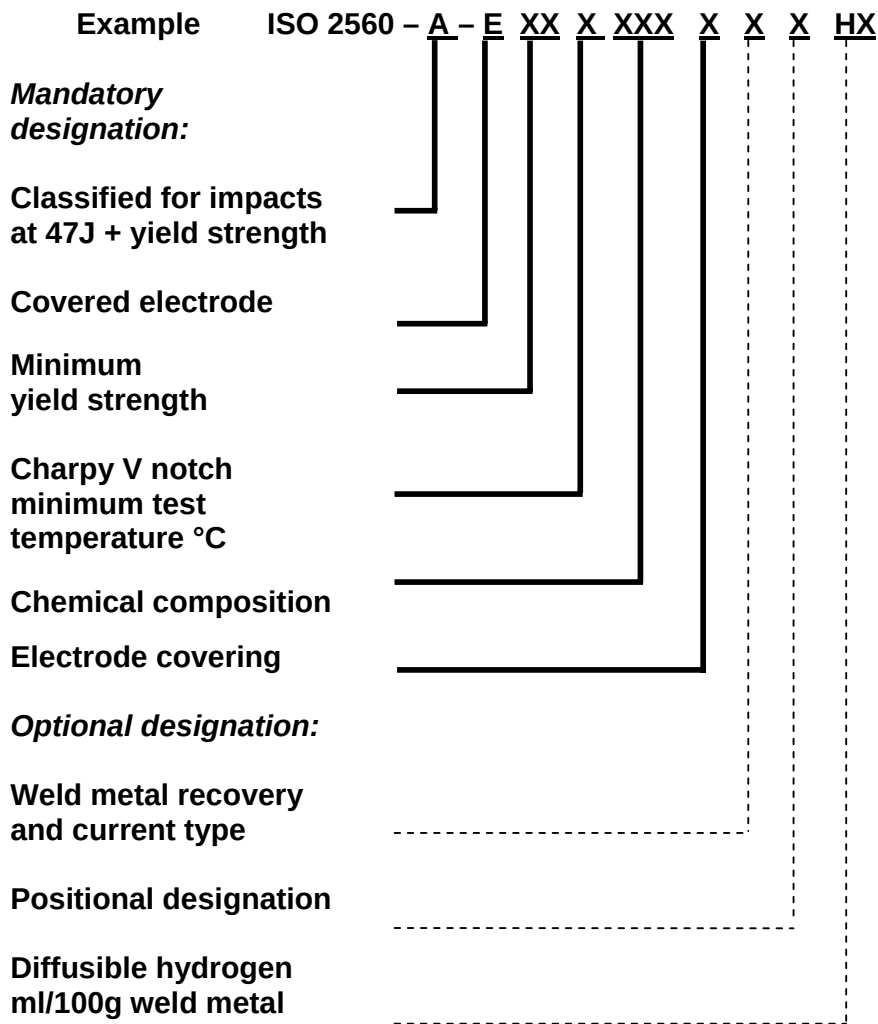
EN ISO 2560 2005 (supersedes BS EN 499 1994)

Classification of Welding Consumables for Covered Electrodes for Manual Metal Arc (111) Welding of Non-alloy and Fine Grain Steels

This standard applies a dual approach to classification of electrodes using methods **A** and **B** as is indicated below:

Classification of electrode mechanical properties of an all weld metal specimen:

Method A: Yield strength and average impact energy at 47J



Typical example: ISO 2560 – A – E 43 2 1Ni RR 6 3 H15

Method B: Tensile strength and average impact energy at 27J

Example	ISO 2560	B	E	XX	XX	XXX	X	X	HX
Mandatory designation:									
Classified for impacts at 27J + tensile strength									
Covered electrode									
Minimum tensile strength									
Electrode covering									
Chemical composition									
Heat treatment condition									
Optional designation:									
Optional supplemental impact test at 47J at same test temperature given for 27J test									
Diffusible hydrogen ml/100g weld metal									
Typical example: ISO 2560 – B – E 55 16 –N7 A U H5									

Classification of tensile characteristics

Method A

Symbol	Minimum yield ^a , N/mm ²	Tensile strength, N/mm ²	Minimum E% ^b , N/mm ²
35	355	440 – 570	22
38	380	470 – 600	20
42	420	500 – 640	20
46	460	530 – 680	20
50	500	560 – 720	18
^a Lower yield R _{el} shall be used. ^b Gauge length = 5 x Ø			

Method B

Symbol	Minimum tensile strength, N/mm ²
43	430
49	490
55	550
57	570

Other tensile characteristics ie **yield strength** and **elongation %** are contained within a tabular form in this standard (**Table 8B**) and are determined by classification of tensile strength, electrode covering and alloying elements, ie **E 55 16-N7**

Classification of impact properties

Method A

Symbol	Temperature for the minimum average impact energy of 47J
Z	No requirement
A	+20
0	0
2	-20
3	-30
4	-40
5	-50
6	-60

Method B

Impact or **Charpy V** notch testing temperature at **27J** temperature in method B is again determined through the classification of tensile strength, electrode covering and alloying elements (**Table 8B**) ie a **E 55 16-N7** which must reach **27J** at **-75°C**.

Classification of electrode characteristics and electrical requirements varies between classification methods A and B as follows:

Method A

This method uses an alpha/numerical designation from the tables as listed below:

Symbol	Electrode covering type
A	Acid
C	Cellulosic
R	Rutile
RR	Rutile thick covering
RC	Rutile/cellulosic
RA	Rutile/acid
RB	Rutile/basic
B	Basic

Symbol	Efficiency, %	Type of current
1	< 105	AC or DC
2	<105	DC
3	>105-<125	AC or DC
4	>105-<125	DC
5	>125-<160	AC or DC
6	>125-<160	DC
7	>160	AC or DC
8	>160	DC

Method B

This method uses a numerical designation from the table as listed below

Symbol	Covering type	Positions	Type of current
03	Rutile/basic	All ^b	AC and DC +/-
10	Cellulosic	All	DC +
11	Cellulosic	All	AC and DC +
12	Rutile	All ^b	AC and DC -
13	Rutile	All ^b	AC and DC +/-
14	Rutile + Fe powder	All ^b	AC and DC +/-
15	Basic	All ^b	DC +
16	Basic	All ^b	AC and DC +
18	Basic + Fe powder	All ^b	AC and DC +
19	Rutile + Fe oxide (Ilmenite)	All ^b	AC and DC +/-
20	Fe oxide	PA/PB	AC and DC -
24	Rutile + Fe powder	PA/PB	AC and DC +/-
27	Fe oxide + Fe powder	PA/PB only	AC and DC -
28	Basic + Fe powder	PA/PB/PC	AC and DC +
40	Not specified	<i>As per manufacturer's recommendations</i>	
48	Basic	All	AC and DC +
^b All positions may or may not include vertical-down welding			

Further guidance on flux type and applications is given in the standard in Annex B and C

Hydrogen scales

Diffusible hydrogen is indicated in the same way in both methods, where after baking the amount of hydrogen is given as **ml/100g weld metal** ie **H 5 = 5ml/100g weld metal**.

AWS A 5.1- and AWS 5.5-

A typical AWS A5.1 and A5.5 Specification E 80 1 8 G
Reference given in box letter: A) B) C) (D For A5.5 only)

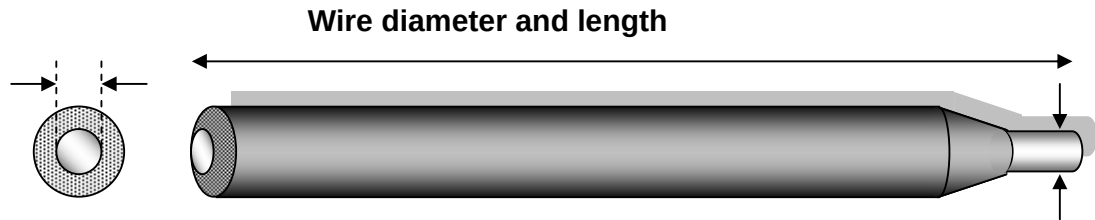
A) Tensile + yield strength and E%				B) Welding position	
Code	Min yield PSI x 1000	Min tensile PSI x 1000	Min E % In 2" min	1	All positional
				2	Flat butt & H/V fillet welds
General				3	Flat only
E 60xx	48,000	60,000	17-22	Note: Not all Category 1 electrodes can weld in the vertical down position.	
E 70xx	57,000	70,000	17-22		
E 80xx	68-80,000	80,000	19-22		
E 100xx	87,000	100,000	13-16		
Specific electrode information for E 60xx and 70xx				V notch impact Izod test (ft.lbs)	Radiographic standard
E 6010	48,000	60,000	22	20 ft.lbs at –20°F	Grade 2
E 6011	48,000	60,000	22	20 ft.lbs at –20°F	Grade 2
E 6012	48,000	60,000	17	Not required	Not required
E 6013	48,000	60,000	17	Not required	Grade 2
E 6020	48,000	60,000	22	Not required	Grade 1
E 6022	Not required	60,000	Not required	Not required	Not required
E 6027	48,000	60,000	22	20 ft.lbs at –20°F	Grade 2
E 7014	58,000	70,000	17	Not required	Grade 2
E 7015	58,000	70,000	22	20 ft.lbs at –20°F	Grade 1
E 7016	58,000	70,000	22	20 ft.lbs at –20°F	Grade 1
E 7018	58,000	70,000	22	20 ft.lbs at –20°F	Grade 1
E 7024	58,000	70,000	17	Not required	Grade 2
E 7028	58,000	70,000	20	20 ft.lbs at 0°F	Grade 2

c) Electrode coating and electrical characteristic		
Code	Coating	Current type
Exx10	Cellulosic/organic	DC + only
Exx11	Cellulosic/organic	AC or DC+
Exx12	Rutile	AC or DC-
Exx13	Rutile + 30% Fe powder	AC or DC+/-
E xx14	Rutile	AC or DC+/-
E xx15	Basic	DC + only
E xx16	Basic	AC or DC+
E xx18	Basic + 25% Fe powder	AC or DC+
E xx20	High Fe oxide content	AC or DC+/-
E xx24	Rutile + 50% Fe powder	AC or DC+/-
E xx27	Mineral + 50% Fe powder	AC or DC+/-
E xx28	Basic + 50% Fe powder	AC or DC+

D) AWS A5.5 low alloy steels	
Symbol	Approximate alloy deposit
A1	0.5%Mo
B1	0.5%Cr + 0.5%Mo
B2	1.25%Cr + 0.5%Mo
B3	2.25%Cr + 1.0%Mo
B4	2.0%Cr+ 0.5%Mo
B5	0.5%Cr + 1.0%Mo
C1	2.5%Ni
C2	3.25%Ni
C3	1%Ni + 0.35%Mo + 0.15%Cr
D1/2	0.25-0.45%Mo + 0.15%Cr
G	0.5%Ni or/and 0.3%Cr or/and 0.2%Mo or/and 0.1%V
For G only 1 element is required	

2 Inspection Points for MMA Consumables

Size



Condition

Cracks, chips and concentricity



All electrodes showing signs of the effects of **corrosion** should be **discarded**.

Type (specification)

Correct specification/code



Storage

Suitably dry and warm
(preferably 0% humidity)

Checks should also be made to ensure that **basic electrodes** have been through the correct **pre-use procedure**. Having been baked to the correct temperature (typically 300-350°C) for **1 hour** and then held in a holding oven (**150°C max**) basic electrodes are issued to the welders in **heated quivers**. Most electrode flux coatings will deteriorate rapidly when damp and care should be taken to inspect storage facilities to ensure that they are adequately dry and that all electrodes are stored in conditions of controlled humidity.

Vacuum packed electrodes may be used directly from the carton only if the vacuum has been maintained. Directions for hydrogen control are always given on the carton and should be strictly adhered to. The cost of each electrode is insignificant compared with the cost of any repair, thus basic electrodes that are left in the heated quiver after the day's shift may potentially be rebaked but would normally be discarded to avoid the risk of H₂ induced problems.

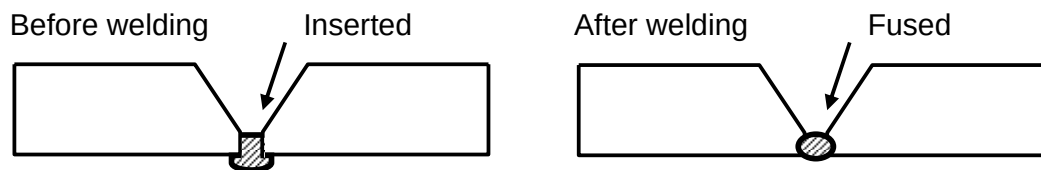
3 Consumables for TIG/GTA Welding (GTAW)

Consumables for TIG/GTAW welding consist of a wire and gas, though tungsten electrodes may also be grouped in this. Though it is considered as a **non-consumable** electrode process, the electrode is consumed by erosion in the arc and by grinding and incorrect welding technique. The wire needs to be of a very high quality as normally no extra cleaning elements can be added to the weld. The wire is refined at the original casting stage to a very high quality where it is then rolled and finally drawn down to the correct size. It is then copper-coated and cut into 1m lengths when a code is then stamped on the wire with a manufacturer's or nationally recognised number for the correct identification of chemical composition. A grade of wire is selected from a table of compositions and wires are mostly copper-coated which inhibits the effects of corrosion. Gases for TIG/GTAW are generally inert and pure argon or helium gases are generally used for TIG welding. The gases are extracted from the air by liquefaction where argon being more common in air is thus generally cheaper than helium.

In the USA helium occurs naturally, thus it is the gas more often used. Helium gas produces a deeper penetrating arc than argon, but is less dense (lighter) than air and needs 2 to 3 times the flow rate of argon gas to produce sufficient cover to the weld area when welding downhand. Argon on the other hand is denser (heavier) than air and thus less gas needs to be used in the downhand position. Mixtures of argon and helium are often used to balance the properties of the arc and the shielding cover ability of the gas. Gases for TIG/GTAW need to be of the highest purity (99.99%). Careful attention and **inspection** should be given to the purging and condition of gas hoses, as it is very possible that contamination of the shielding gas can occur due to a worn or withered hose.

Tungsten electrodes for TIG welding are generally produced by powder forging technology. The electrodes contain other oxides to increase their conductivity and electron emission and also affect the characteristics of the arc. Tungsten electrodes are available off the shelf 1.6-10mm diameter. Ceramic shields may also be considered as a consumable item as they are easily broken, the size and shape of ceramic depending mainly on the type of joint design and the diameter of the tungsten.

A particular consumable item that may be used during the **TIG welding of pipes** is a **fusible insert** often referred to as an **EB insert** after the **Electric Boat Co of USA** who first developed it. The insert is normally made of material matching the pipe base metal composition and is fused into the root during welding as shown below.



4 Consumables for MIG/MAG Welding

Consumables for MIG/MAG welding consist of a wire and gas. The wire specifications used for TIG are also used for MIG/MAG welding as a similar level of quality is required in the wire.

The main purpose of the copper coating of steel MIG/MAG welding wire is to maximise current pick-up at the contact tip and reduce the level of coefficient of friction in the liner with protection against the effects of corrosion being a secondary function.

Wires are available that have not been copper-coated as the effects of copper flaking in the liner can cause many wire feed problems. These wires may be coated in a graphite compound, which again increases current pick-up and reduces friction in the liner. Some wires, including many cored wires, are nickel coated.

Wires are available in sizes from 0.6-1.6mm diameter with finer wires available on a 1kg reel, though most wires are supplied on a 15kg drum.

Common gases and mixtures used for MIG/MAG welding include:

Gas type	Process	Used for	Characteristic
Pure argon	MIG	Spray or pulse welding of aluminium alloys	Very stable arc with poor penetration and low spatter levels.
Pure CO ₂	MAG	Dip transfer welding of steels	Good penetration , unstable arc and high levels of spatter.
Argon + 5-20% CO ₂	MAG	Dip spray or pulse welding of steels	Good penetration with a stable arc and low levels of spatter.
Argon + 1-2% O ₂ or CO ₂	MAG	Spray or pulse welding of austenitic or ferritic stainless steels only	Active additive gives good fluidity to the molten stainless, and improves toe blend.

5 Consumables for SAW Welding

Consumables for SAW consist of an electrode wire and flux. Electrode wires are normally of high quality and for welding C-Mn steels are generally graded on their increasing carbon and manganese content level of de-oxidation.

Electrode wires for welding other alloy steels are generally graded by chemical composition in a table in a similar way to MIG and TIG electrode wires. Fluxes for SAW are graded by their manufacture and composition. There are two normal methods of manufacture known as **fused** and **agglomerated**.

Fused fluxes

Fused fluxes are mixed together and baked at a very high temperature ($>1,000^{\circ}\text{C}$), where all the components fuse together. When cooled the resultant mass resembles a sheet of coloured glass, which is then pulverised into small particles.

These particles are hard, reflective, irregularly-shaped and cannot be crushed in the hand. It is impossible to incorporate certain alloying compounds into the flux such as ferro-manganese as these would be destroyed in the high temperatures of the manufacturing process. Fused fluxes tend to be of the **acidic type** and are fairly tolerant of poor surface conditions, but produce comparatively low quality weld metal in terms of the mechanical properties of tensile strength and toughness. They are easy to use and produce a good weld contour with an easily detachable slag.



Agglomerated fluxes

Agglomerated fluxes are a mixture of compounds baked at a much lower temperature and are essentially bonded together by bonding agents into small particles. The recognition points of these types of fluxes is easier, as they are dull, generally round granules that are friable (easily crushed) and can also be coloured. Many agents and compounds may be added during manufacture unlike the fused fluxes. Agglomerated fluxes tend to be of the *basic type* and will produce weld metal of an improved quality in terms of strength and toughness, at the expense of usability as these fluxes are much less tolerant of poor surface conditions and generally produce a slag much more difficult to detach and remove.



It can be seen that the weld metal properties will result from using a particular wire, with a particular flux, in a particular weld sequence and therefore the grading of SAW consumables is given as a function of a **wire/flux combination and welding sequence**.

A typical grade will give values for:

- Tensile strength.
- Elongation, %.
- Toughness, Joules.
- Toughness testing temperature.

All consumables for SAW (wires and fluxes) should be stored in a dry and humid-free atmosphere. The flux manufacturer's handling/storage instructions/conditions should be very strictly followed to minimise any moisture pick-up. Any re-use of fluxes is totally dependant on applicable clauses within the application standard.

On no account should different types of fluxes be mixed.

Exercises

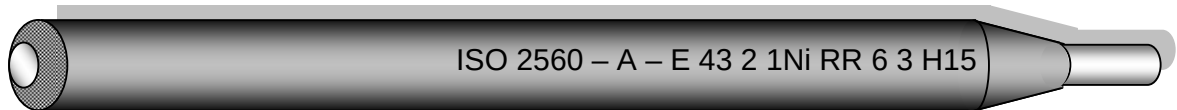
List/comment on four main inspection points of MMA welding consumables

1. Size: Wire diameter and length of electrodes
2. _____
3. _____
4. _____

Complete the table of general information below.

Group	Constituent	Shield gas	Uses	AWS A 5.1
Rutile				E 6013
	Calcium compounds		High quality	
		Hydrogen + CO ₂		

Indicate the *main information* given on the electrode below to BS EN 2560



- | | |
|---|------------------|
| A <u>Yield and impact at 47J</u> | E _____ |
| 43 _____ | 2 _____ |
| 2 _____ | 1Ni _____ |
| RR _____ | 6 _____ |
| 3 _____ | H15 _____ |

Identify a positive recognition point of a fused/agglomerated SAW flux?

Fused:

Agglomerated:

1. _____

1. _____

Complete the table of information below for MIG/MAG welding gases?

Argon + 5-20% CO ₂		Dip spray or pulse Welding of steels	
	MAG		Gives <i>fluidity</i> to molten <i>stainless</i> <i>improving</i> the weld <i>toe blend</i>

1 Introduction

The term weldability simply means the ability to be welded and many types of steel that are weldable have been developed for a wide range of applications.

However, it is the ease or difficulty of making a weld with suitable properties and free from defects which determines whether steels are considered as having good or poor weldability. A steel is usually said to have poor weldability if it is necessary to take special precautions to avoid a particular type of imperfection. Another reason for poor weldability may be the need to weld within a very narrow range of parameters to achieve properties required for the joint.

2 Factors That Affect Weldability

A number of inter-related factors determine whether a steel is said to have good or poor weldability. These are:

- **Actual** chemical composition.
- Weld joint configuration.
- Welding process to be used.
- The properties required from the weldment.

For steels with poor weldability it is particularly necessary to ensure that:

- WPSs give welding conditions that do not cause cracking but achieve the specified properties.
- Welders work strictly in accordance with the specified welding conditions
- Welding inspectors regularly monitor welders to ensure they are working strictly in accordance with the WPSs.

Having a good understanding of the characteristics, causes, and ways of avoiding imperfections in steel weldments should enable welding inspectors to focus attention on the most influential welding parameters when steels with poor weldability are being used.

3 Hydrogen Cracking

During fabrication by welding, cracks can occur in some types of steel, due to the presence of hydrogen. The technical name for this type of cracking is **hydrogen induced cold cracking (HICC)** but it is often referred to by other names that describe various characteristics of hydrogen cracks:

- Cold cracking Cracks occur when the weld has cooled down.
- HAZ cracking Cracks tend to occur mainly in the HAZ.
- Delayed cracking Cracks may occur some time after welding has finished (possibly up to ~72h).
- Underbead cracking Cracks occur in the HAZ beneath a weld bead.

Although most hydrogen cracks occur in the HAZ, there are circumstances when they may form in weld metal.

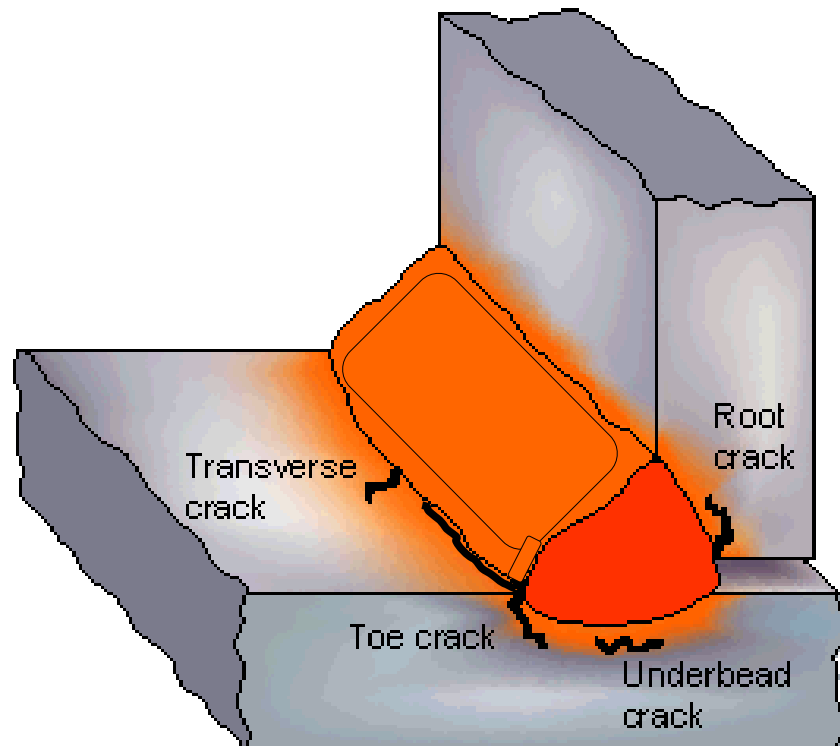


Figure 1 Schematic showing typical locations of hydrogen induced cold cracks.

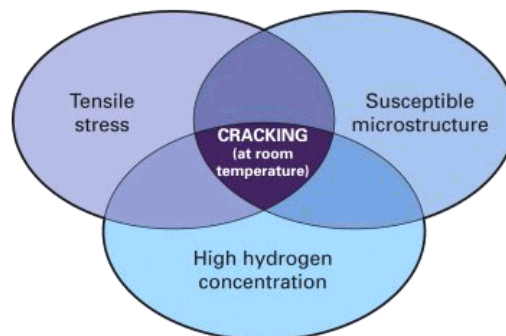


Figure 2 A hydrogen induced cold crack that initiated the HAZ at the toe of a fillet weld.

3.1 Factors influencing susceptibility to hydrogen cracking

Hydrogen cracking in the HAZ of a steel occurs when **four conditions exist at the same time**:

- Hydrogen level >15ml/100g of weld metal deposited
- Stress >0.5 of the yield stress
- Temperature <300°C
- Susceptible microstructure >400HV hardness



These four conditions (factors) are mutually interdependent so that the influence of one condition (its' active level) depends on how active the others three factors are.

3.2 Cracking mechanism

Hydrogen (H) can enter the molten weld metal when hydrogen-containing molecules are broken down into H atoms in the welding arc.

Because H atoms are very small they can move about (diffuse) in solid steel and while weld metal is hot they can diffuse to the weld surface and escape into the atmosphere.

However, at lower temperatures H cannot diffuse as quickly and if the weldment cools down quickly to ambient temperature H will become trapped – usually in the HAZ.

If the HAZ has a susceptible microstructure – indicated by being relatively hard and brittle, and there are also relatively high tensile stresses in the weldment – then H cracking can occur.

The precise mechanism that causes cracks to form is complex but H is believed to cause embrittlement of regions of the HAZ so that high localised stresses cause cracking rather than plastic straining.

3.3 Avoiding HAZ hydrogen cracking

Because the factors that cause cracking are interdependent, and each need to be at an active level at the same time, cracking can be avoided by ensuring that at least one of the four factors is **not active** during welding.

Methods that can be used to minimise the influence of each of the four factors are considered in the following sub-sections.

Hydrogen

The main source of hydrogen is moisture (H_2O) and the principal source of moisture is welding flux. Some fluxes contain cellulose and this can be a very active source of hydrogen.

Welding processes that do not require flux can be regarded as low hydrogen processes.

Other sources of hydrogen are moisture present in rust or scale, and oils and greases (hydrocarbons).

Reducing the influence of hydrogen is possible by:

- Ensuring that fluxes (coated electrodes, flux cored wires and SAW fluxes) are low in H when welding commences.
- Low H electrodes must be either baked and then stored in a hot holding oven or supplied in vacuum-sealed packages.
- Basic agglomerated SAW fluxes should be kept in a heated silo before issue to maintain their as-supplied, low moisture, condition.
- Checking the diffusible hydrogen content of the weld metal (sometimes it is specified on the test certificate).
- Ensuring that a low H condition is maintained throughout welding by not allowing fluxes to pick up moisture from the atmosphere.
- Low hydrogen electrodes must be issued in small quantities and the exposure time limited; heated quivers facilitate this control.
- Flux cored wire spools that are not seamless should be covered or returned to a suitable storage condition when not in use.
- Basic agglomerated SAW fluxes should be returned to the heated silo when welding is not continuous.
- Checking the amount of moisture present in the shielding gas by checking the dew point (must be below $-60^{\circ}C$).
- Ensuring that the weld zone is dry and free from rust/scale and oil/grease.

Tensile stress

There are always tensile stresses acting on a weld because there are always residual stresses from welding.

The magnitude of the tensile stresses is mainly dependent on the thickness of the steel at the joint, heat input, joint type, and the size and weight of the components being welded.

Tensile stresses in highly restrained joints may be as high as the yield strength of the steel and this is usually the case in large components with thick joints and it is not a factor that can easily be controlled.

The only practical ways of reducing the influence of residual stresses may be by:

- Avoiding stress concentrations due to poor fit-up.
- Avoiding poor weld profile (sharp weld toes).
- Applying a stress relief heat treatment after welding.
- Increasing the travel speed as practicable in order to reduce the heat input.
- Keeping weld metal volume as low a level as possible.

These measures are particularly important when welding some low alloy steels that are particularly sensitive to hydrogen cracking.

Susceptible HAZ microstructure

A susceptible HAZ microstructure is one that contains a relatively high proportion of hard brittle phases of steel – particularly martensite.

The HAZ hardness is a good indicator of susceptibility and when it exceeds a certain value that steel is considered to be susceptible. For C and C-Mn steels this hardness value is ~350HV and susceptibility to H cracking increases as hardness increases above this value.

The maximum hardness of an HAZ is influenced by:

- Chemical composition of the steel.
- Cooling rate of the HAZ after each weld run is made.

For C and C-Mn steels a formula has been developed to assess how the chemical composition will influence the tendency for significant HAZ hardening – the carbon equivalent value (CEV) formula.

The CEV formula most widely used (and adopted by IIW) is:

$$CEV_{iww} = \%C + \frac{\%Mn}{6} + \frac{\%Cr + \%Mo + \%V}{5} + \frac{\%Ni + \%Cu}{15}$$

The CEV of a steel is calculated by inserting the material test certificate values shown for chemical composition into the formula. The higher the CEV the greater its susceptibility to HAZ hardening and therefore the greater the susceptibility to H cracking.

The element with most influence on HAZ hardness is carbon. The faster the rate of HAZ cooling after each weld run, the greater the tendency for hardening.

Cooling rate tends to increase as:

- Heat input decreases (lower energy input).
- Joint thickness increases (bigger heat sink).

Avoiding a susceptible HAZ microstructure (for C and C-Mn steels) requires:

- Procuring steel with a CEV that is at the low end of the range for the steel grade (limited scope of effectiveness).
- Using moderate welding heat input so that the weld does not cool quickly (and give HAZ hardening).
- Applying preheat so that the HAZ cools more slowly (and does not show significant HAZ hardening); in multi-run welds, maintain a specific interpass temperature.

For low alloy steels, with additions of elements such as Cr, Mo and V, the CEV formula is not applicable and so must not be used to judge the susceptibility to hardening. The HAZ of these steels will always tend to be relatively hard regardless of heat input and preheat and so this is a factor that cannot be effectively controlled to reduce the risk of H cracking. This is the reason why some of the low alloy steels have a greater tendency to show hydrogen cracking than in weldable C and C-Mn steels, which enable HAZ hardness to be controlled.

Weldment at low temperature

Weldment temperature has a major influence on susceptibility to cracking mainly by influencing the rate at which H can move (diffuse) through the weld and HAZ. While a weld is relatively warm ($> \sim 300^{\circ}\text{C}$) H will diffuse quite rapidly and escape into the atmosphere rather than be trapped and cause embrittlement.

Reducing the influence of low weldment temperature (and the risk of trapping H in the weldment) can be effected by:

- Applying a suitable preheat temperature (typically 50 to $\sim 250^{\circ}\text{C}$).
- Preventing the weld from cooling down quickly after each pass by maintaining the preheat and the specific interpass temperature during welding
- Maintaining the preheat temperature (or raising it to $\sim 250^{\circ}\text{C}$) when welding has finished and holding the joint at this temperature for a number of hours (minimum two hours) to facilitate the escape of H (called post-heat)
- Post-heat. It must not be confused with PWHT at a temperature $\geq \sim 600^{\circ}\text{C}$.

3.4 Hydrogen cracking in weld metal

Hydrogen cracks can form in steel weld metal under certain circumstances. The mechanism of cracking and identification of all the influencing factors is less clearly understood than for HAZ cracking but it can occur when welding conditions cause H to become trapped in weld metal rather than in HAZ. However, it is recognised that welds in higher strength materials, thicker sections and using large beads are the most common areas where problems arise.

Hydrogen cracks in weld metal usually lie at 45° to the direction of principal tensile stress in the weld metal and this is usually the longitudinal axis of the weld (Figure 3). In some cases the cracks are of a V formation, hence an alternative name chevron cracking.

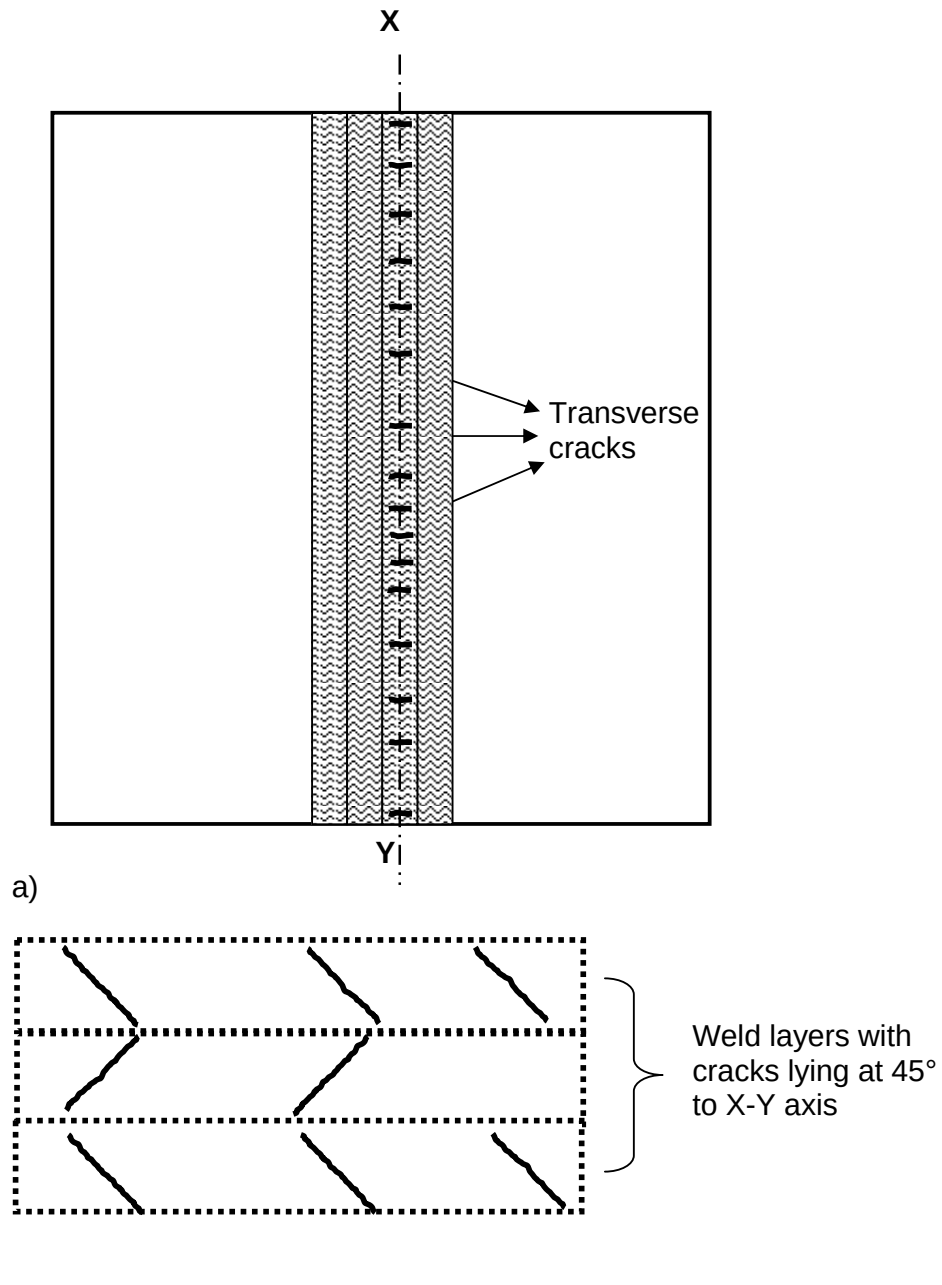


Figure 3:

- a) Plan view of a plate but weld showing subsurface transverse cracks.
- b) Longitudinal section X-Y of the above weld showing how the transverse cracks lie at 45° to the surface. They tend to remain within an individual weld run and may be in weld several layers.

Their appearance in this orientation has given rise to the name chevron cracks (arrow shaped cracks). There are not any well defined rules for avoiding weld metal hydrogen cracks apart from:

- Ensure a low hydrogen welding process is used.
- Apply preheat and maintain a specific interpass temperature.

BS EN 1011-2 'Welding – Recommendations for welding of metallic materials – Part 2: Arc welding of ferritic steels' gives in Annex C practical guidelines about how to avoid H cracking. Practical controls are based principally on the application of preheat and control of potential H associated with the welding process.

4 Solidification Cracking

The technically correct name for cracks that form during weld metal solidification is solidification cracks but other names are sometimes used:

- Hot cracking: They occur at high temperatures while the weld is hot.
- Centreline cracking: Cracks may appear down the centreline of the weld bead.
- Crater cracking: Small cracks in weld craters are solidification cracks.

Because a weld metal may be particularly susceptible to solidification cracking it may be said to show hot shortness because it is short of ductility when hot and so tends to crack.

Figure 4 shows a transverse section of a weld with a typical centreline solidification crack.

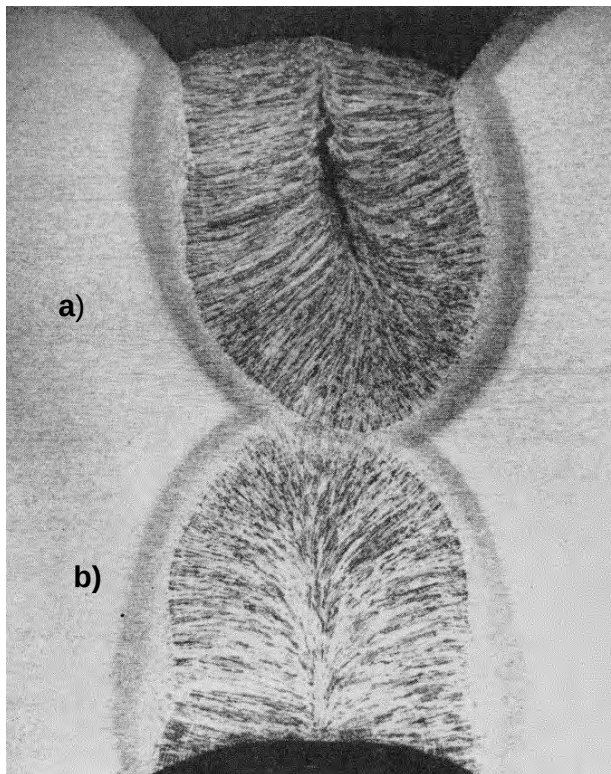


Figure 4:

- a) Solidification crack at the weld centre where columnar dendrites have trapped some lower melting point liquid;
- b) The weld bead does not have an ideal shape but it has solidified without the dendrites meeting end-on and trapping lower melting point liquid thereby resisting solidification cracking

4.1 Factors influencing susceptibility to solidification cracking

Solidification cracking occurs when **three conditions exist at the same time**:

- Weld metal has a susceptible chemical composition.
- Welding conditions used give an unfavourable bead shape.
- High level of restraint or tensile stresses present in the weld area.

4.2 Cracking mechanism

All weld metals solidify over a temperature range and since solidification starts at the fusion line towards the centreline of the weld pool, during the last stages of weld bead solidification there may be enough liquid present to form a weak zone in the centre of the bead. This liquid film is the result of low melting point constituents being pushed ahead of the solidification front.

During solidification, tensile stresses start to build up due to contraction of the solid parts of the weld bead, and it is these stresses that can cause the weld bead to rupture. These circumstances result in a weld bead showing a centreline crack that is present as soon as the bead has been deposited.

Centreline solidification cracks tend to be surface breaking at some point in their length and can be easily seen during visual inspection because they tend to be relatively wide cracks.

4.3 Avoiding solidification cracking

Avoiding solidification cracking requires the influence of one of the factors responsible, to be reduced to an inactive level.

Weld metal composition

Most C and C-Mn steel weld metals made by modern steelmaking methods do not have chemical compositions that are particularly sensitive to solidification cracking. However, these weld metals can become sensitive to this type of cracking if they are contaminated with elements, or compounds, that produce relatively low melting point films in weld metal.

Sulphur and copper are elements that can make steel weld metal sensitive to solidification cracking if they are present in the weld at relatively high levels. Sulphur contamination may lead to the formation of iron sulphides that remain liquid when the bead has cooled down as low as $\sim 980^{\circ}\text{C}$, whereas bead solidification started at above 1400°C .

The source of sulphur may be contamination by oil or grease or it could be picked up from the less refined parent steel being welded by dilution into the weld.

Copper contamination in weld metal can be similarly harmful because it has low solubility in steel and can form films that are still molten at $\sim 1100^{\circ}\text{C}$.

Avoiding solidification cracking (of an otherwise non-sensitive weld metal) requires the avoidance of contamination with potentially harmful materials by ensuring:

- Weld joints are thoroughly cleaned immediately before welding.
- Any copper containing welding accessories are suitable/in suitable condition – such as backing-bars and contact tips used for GMAW, FCAW and SAW.

Unfavourable welding conditions

Unfavourable welding conditions are those that encourage weld beads to solidify so that low melting point films become trapped at the centre of a solidifying weld bead and become the weak zones for easy crack formation.

Figure 5 shows a weld bead that has solidified using unfavourable welding conditions associated with centreline solidification cracking.

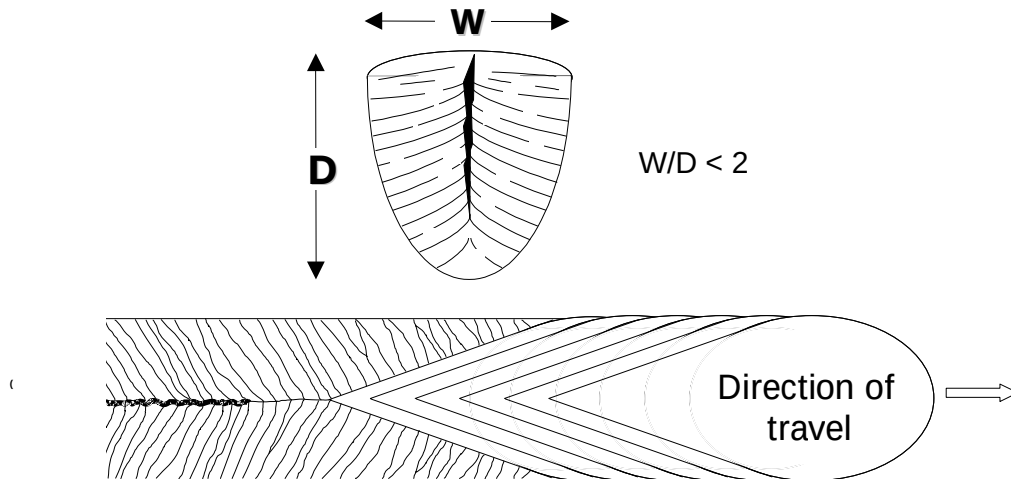


Figure 5 A weld bead with an unfavourable width-to-depth ratio. This is responsible for liquid metal being pushed into the centre of the bead by the advancing columnar dendrites and becoming the weak zone that ruptures.

The weld bead has a cross-section that is quite deep and narrow – a width-to-depth ratio $< \sim 2$ and the solidifying dendrites have pushed the lower melting point liquid to the centre of the bead where it has become trapped. Since the surrounding material is shrinking as a result of cooling, this film would be subjected to tensile stress, which leads to cracking.

In contrast, Figure 6 shows a bead that has a width-to-depth ratio that is $\gg 2$. This bead shape shows lower melting point liquid pushed ahead of the solidifying dendrites but it does not become trapped at the bead centre. Thus, even under tensile stresses resulting from cooling, this film is self-healing and cracking is avoided.

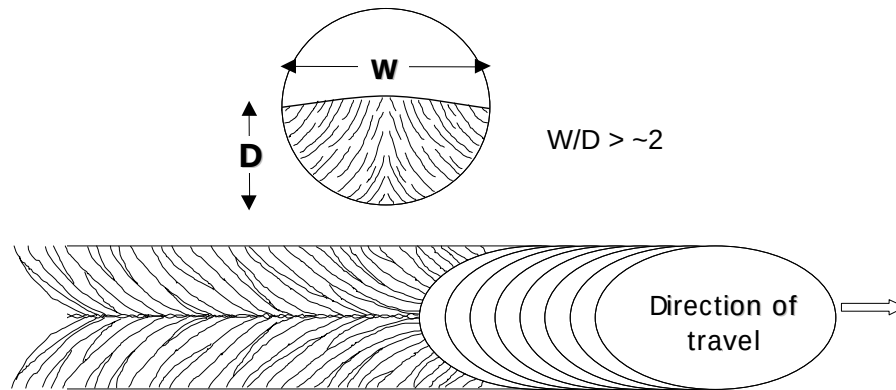


Figure 6 A weld bead with a favourable width-to-depth ratio. The dendrites push the lowest melting point metal towards the surface at the centre of the bead centre so it does not form a weak central zone.

SAW and spray-transfer GMAW are more likely to give weld beads with an unfavourable width-to-depth ratio than the other arc welding processes. Also, electron beam and laser welding processes are extremely sensitive to this kind of cracking as a result of the deep, narrow beads produced.

Avoiding unfavourable welding conditions that lead to centreline solidification cracking (of weld metals with sensitive compositions) may require significant changes to welding parameters, such as reducing:

- Welding current (to give a shallower bead).
- Welding speed (to give a wider weld bead).

Avoiding unfavourable welding conditions that lead to crater cracking of a sensitive weld metal requires changes to the technique used at the end of a weld when the arc is extinguished, such as:

- For TIG welding, use a current slope-out device so that the current and weld pool depth gradually reduce before the arc is extinguished (gives more favourable weld bead width-to-depth ratio). It is also a common practice to backtrack the bead slightly before breaking the arc or lengthen the arc gradually to avoid the crater cracks.
- For TIG welding, modify weld pool solidification mode by feeding the filler wire into the pool until solidification is almost complete and avoiding a concave crater.

- For MMA, modify the weld pool solidification mode by reversing the direction of travel at the end of the weld run so that crater is filled.

5 Lamellar Tearing

Lamellar tearing is a type of cracking that occurs only in steel plate or other rolled products underneath a weld.

Characteristics of lamellar tearing are:

- Cracks only occur in the rolled products, eg plate and sections.
- Most common in C-Mn steels
- Cracks usually form close to, but just outside, the HAZ
- Cracks tend to lie parallel to the surface of the material (and the fusion boundary of the weld), having a stepped aspect.

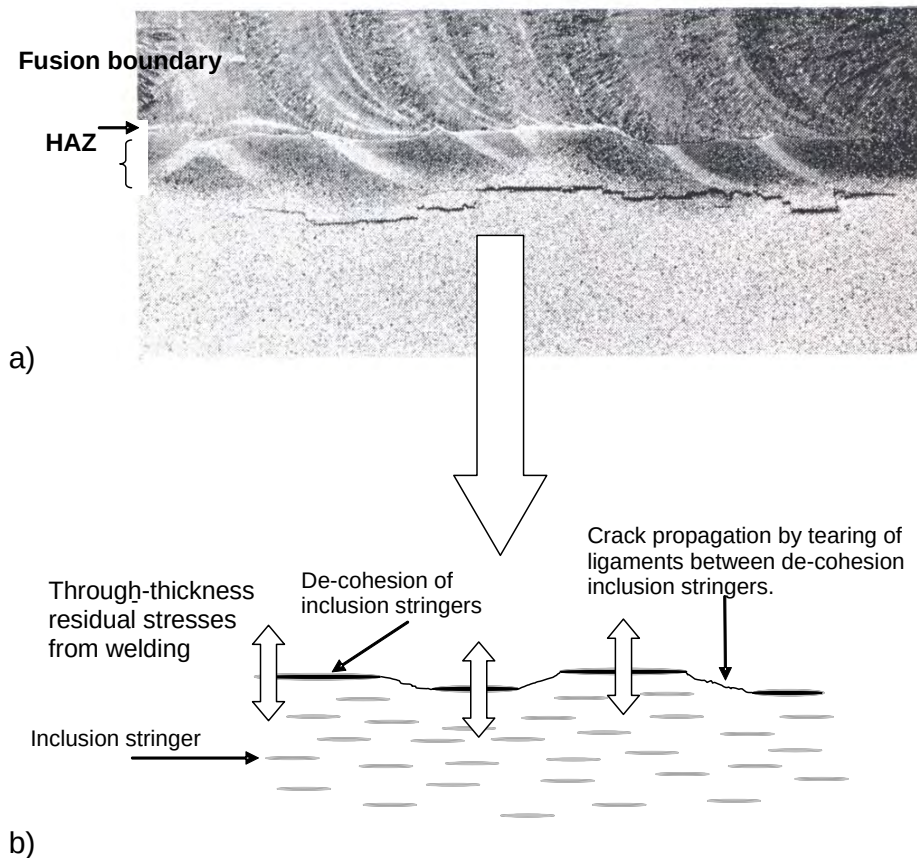


Figure 7:

a) Typical lamellar tear located just outside the visible HAZ.

b) The step-like crack that is characteristic of a lamellar tear.

5.1 Factors influencing susceptibility to lamellar tearing

Lamellar tearing occurs when **two conditions exist at the same time**:

- A susceptible rolled plate is used to make a weld joint.
- High stresses act in the through-thickness direction of the susceptible material (known as the short-transverse direction).

Susceptible rolled plate

A material that is susceptible to lamellar tearing has very low ductility in the through-thickness direction (short-transverse direction) and is only able to accommodate the residual stresses from welding by tearing rather than by plastic straining.

Low through-thickness ductility in rolled products is caused by the presence of numerous non-metallic inclusions in the form of elongated stringers. The inclusions form in the ingot but are flattened and elongated during hot rolling of the material.

Non-metallic inclusions associated with lamellar tearing are principally manganese sulphides and silicates.

High through-thickness stress

Weld joints that are T, K and Y configurations end up **with a tensile residual stress component in the through-thickness direction**.

The magnitude of the through-thickness stress increases as the restraint (rigidity) of the joint increases. Section thickness and size of weld are the main influencing factors and it is in thick section, full penetration T, K and Y joints that lamellar tearing is more likely to occur.

5.2 Cracking mechanism

High stresses in the through-thickness direction that are present as welding residual stresses, cause the inclusion stringers to open-up (de-cohese) and the thin ligaments between individual de-cohased inclusions then tear and produce a stepped crack.

5.3 Avoiding lamellar tearing

Lamellar tearing can be avoided by reducing the influence of one, or both of the factors.

Susceptible rolled plate

EN 10164 (Steel products with improved deformation properties perpendicular to the surface of the product – Technical delivery conditions) gives guidance on the procurement of plate to resist lamellar tearing.

Resistance to lamellar tearing can be evaluated by means of tensile test pieces taken with their axes perpendicular to the plate surface (the through-thickness direction). Through-thickness ductility is measured as the % reduction of area (%R of A) at the point of fracture of the tensile test piece (Figure 8).

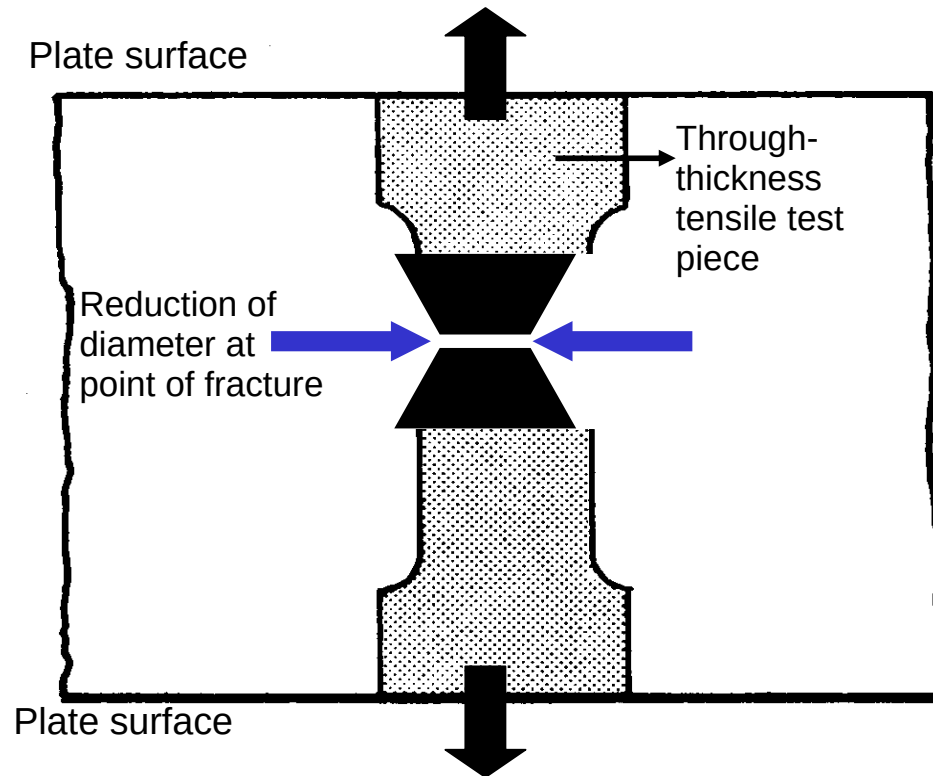


Figure 8 Round tensile test piece taken with its axis in the short-transverse direction (through-thickness of plate) to measure the %R of A and assess the plates resistance to lamellar tearing.

The greater the measured %R of A, the greater the resistance to lamellar tearing. Values in excess of ~20% indicate good resistance even in very highly constrained joints.

Reducing the susceptibility of rolled plate to lamellar tearing can be achieved by ensuring that it has good through-thickness ductility by:

- Using clean steel that has low sulphur content (<~0.015%) and consequently has relatively few inclusions.
- Procuring steel plate that has been subjected to through-thickness tensile testing to demonstrate good through-thickness ductility (as EN 10164).

Through-thickness stress

Through-thickness stress in T, K and Y joints is principally the residual stress from welding, although the additional service stress may have some influence.

Reducing the magnitude of through-thickness stresses for a particular weld joint would require modification to the joint in some way, and so may not always be practical because of the need to satisfy design requirements. However, methods that could be considered are:

Reducing the size of the weld by:

- Using a partial butt weld instead of full-penetration
- Using fillet welds instead of a full, or partial penetration butt weld (Figure 9)

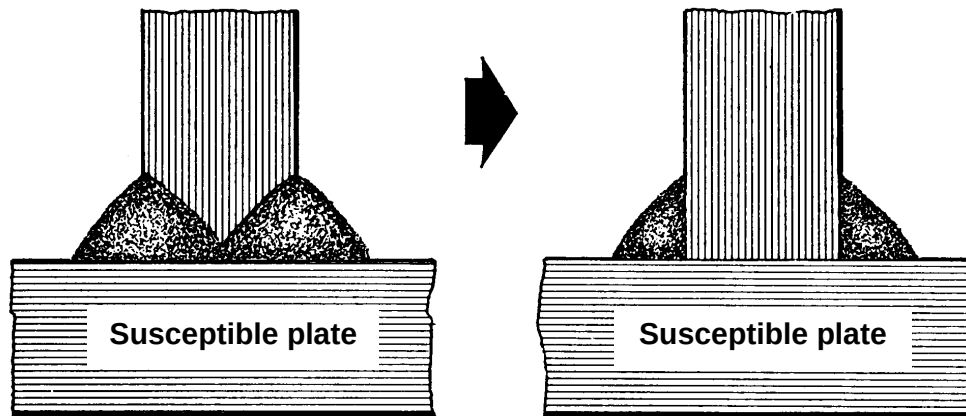


Figure 9 Reducing the effective size of a weld will reduce the through-thickness stress on the susceptible plate and may be sufficient to reduce the risk of lamellar tearing.

- By applying a buttering layer of weld metal to the surface of a susceptible plate so that the highest through-thickness strain is located in the weld metal and not the susceptible plate (Figure 10).

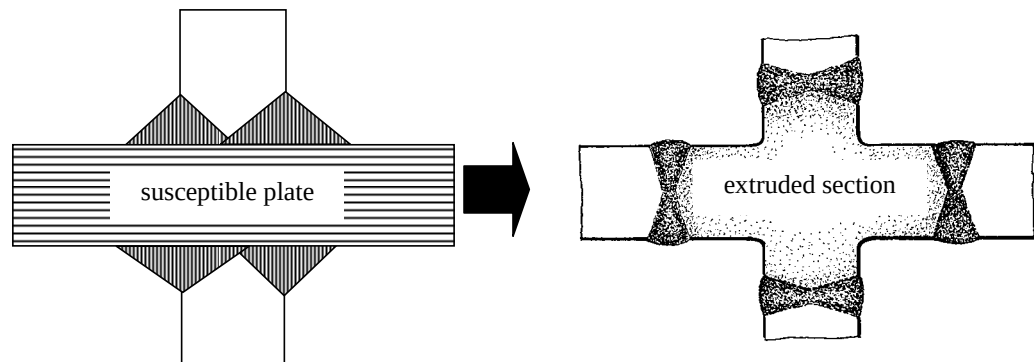


Figure 10 Lamellar tearing can be voided by changing the joint design.

- Changing the joint design – such as using a forged or extruded intermediate piece so that the susceptible plate does not experience through-thickness stress (Figure 11).

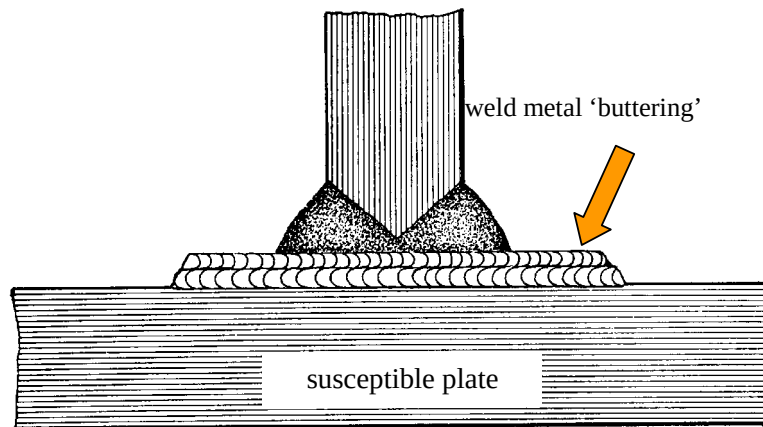


Figure 11 Two layers of weld metal (usually by MMA) applied to susceptible plate before the T-butt is made.

Weld repairs can be divided into two specific areas:

1 Production

2 In-service

The reasons for making a repair are many and varied, from the removal of weld defects induced during manufacture to a quick and temporary running-repair to an item of production plant. In these terms, the subject of welding repairs is also wide and varied and often confused with maintenance and refurbishment where the work can be scheduled.

With planned maintenance and refurbishment, sufficient time can be allowed to enable the tasks to be completed without production pressures being applied. In contrast, repairs are usually unplanned and may result in shortcuts being taken to allow the production programme to continue. It is, therefore, advisable for a fabricator to have an established policy on repairs and to have repair methods and procedures in place.

The manually controlled welding processes are the easiest to use, particularly if it is a local repair or one to be carried out on site. Probably the most frequently used of these processes is MMA as this is versatile, portable and readily applicable to many alloys because of the wide range of off-the-shelf consumables. Repairs almost always result in higher residual stresses and increased distortion compared with first time welds. With C-Mn and low/medium alloy steels, the application of pre- and postweld heat treatments may be required.

There are a number of key factors that need to be considered before undertaking any repair. The most important being a judgement as to whether it is financially worthwhile. Before this judgement can be made, the fabricator needs to answer the following questions:

- Can structural integrity be achieved if the item is repaired?
- Are there any alternatives to welding?
- What caused the defect and is it likely to happen again?
- How is the defect to be removed and what welding process is to be used?
- Which NDT method is required to ensure complete removal of the defect?
- Will the welding procedures require approval/re-approval?
- What will be the effect of welding distortion and residual stress?
- Will heat treatment be required?
- What NDT is required and how can acceptability of the repair be demonstrated?
- Will approval of the repair be required – if yes, how and by whom?

Although a weld repair may be a relatively straightforward activity, in many instances it can be quite complex and various engineering disciplines may need to be involved to ensure a successful outcome.

It is recommended that ongoing analysis of the types of defect is carried out by the QC department to discover the likely reason for their occurrence (material/process or skill related).

In general terms, a welding repair involves:

- A detailed assessment to find out the extremity of the defect. This may involve the use of a surface or sub-surface NDT method.
- Cleaning the repair area, (removal of paint grease etc).
- Once established the excavation site must be clearly identified and marked out.
- An excavation procedure may be required (method used ie grinding, arc/air gouging, preheat requirements etc).
- NDT to locate the defect and confirm its removal.
- A welding repair procedure/method statement with the appropriate* welding process, consumable, technique, controlled heat input and interpass temperatures, etc will need to be approved.
- Use of approved welders.
- Dressing the weld and final visual.
- NDT procedure/technique prepared and carried out to ensure that the defect has been successfully removed and repaired.
- Any post repair heat treatment requirements.
- Final NDT procedure/technique prepared and carried out after heat treatment requirements.
- Applying protective treatments (painting etc as required).

*Appropriate means suitable for the alloys being repaired and may not apply in specific situations.

Production repairs

Repairs are usually identified during production inspection. Evaluation of the reports is carried out by the Welding Inspector, or NDT operator. Discontinuities in the welds are only classed as defects when they are outside the range permitted by the applied code or standard.

Before the repair can commence, a number of elements need to be fulfilled.

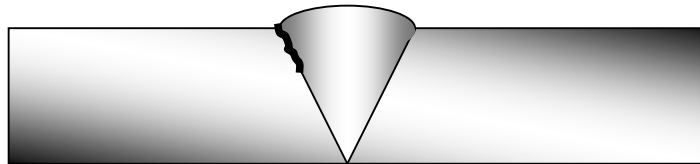
Analysis

As this defect is surface-breaking and has occurred at the fusion face the problem could be cracking or lack of sidewall fusion. If the defect is found to be cracking the cause may be associated with the material or the welding procedure, however if the defect is lack of sidewall fusion this can be apportioned to the lack of skill of the welder.

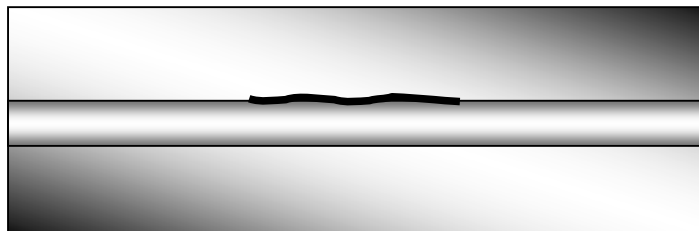
Assessment

In this particular case as the defect is open to the surface, magnetic particle inspection (MPI) or dye penetrant inspection (DPI) may be used to gauge the length of the defect and ultrasonic testing (UT) used to gauge the depth.

A typical defect is shown below:



Plan view of defect



Excavation

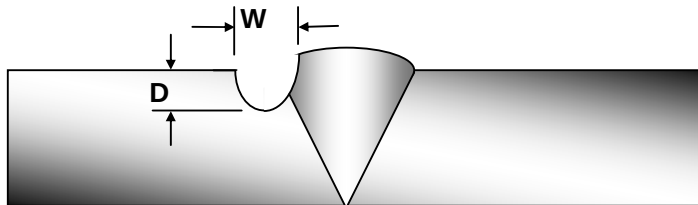
If a thermal method of excavation is being used ie arc/air gouging it may be a requirement to qualify a procedure as the heat generated may have an effect on the metallurgical structure, resulting in the risk of cracking in the weld or parent material.



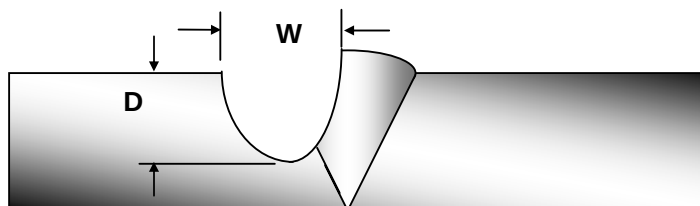
To prevent cracking it may be necessary to apply a preheat.

The depth to width ratio shall not be less than 1 (depth) to 1 (width), ideally 1 (depth) to 1.5 (width) would be recommended (ratio: depth 1 to width 1.5)

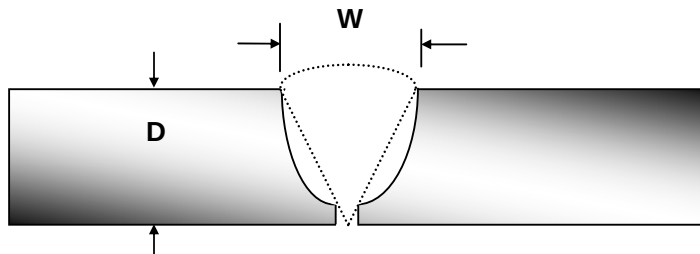
Side view of excavation for slight sub-surface defect



Side view of excavation for deep defect



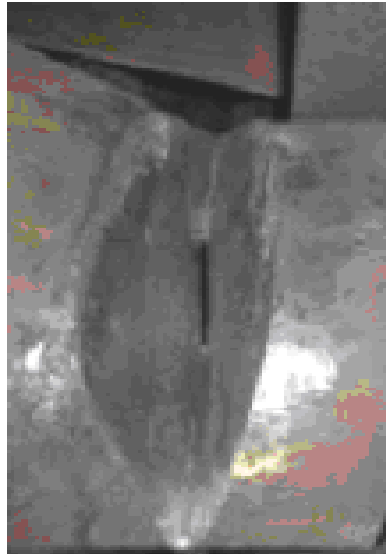
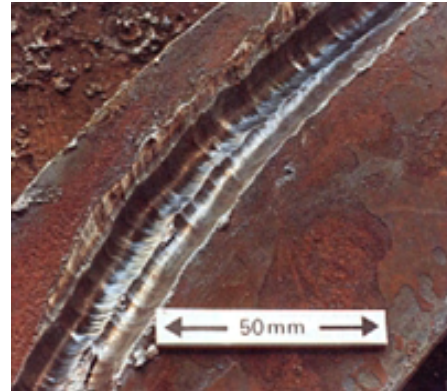
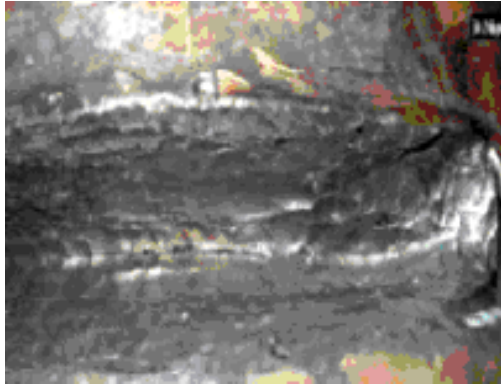
Side view of excavation for full root repair



Cleaning of the excavation

At this stage grinding of the repair area is important, due to the risk of carbon becoming impregnated into the weld metal/parent material.

It should be ground back typically 3 to 4mm to bright metal.

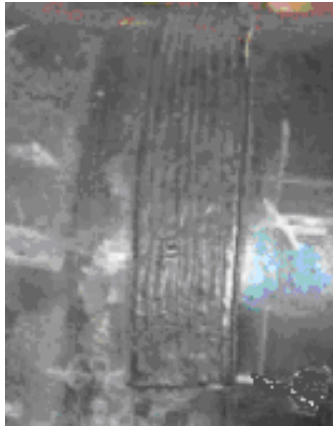


Confirmation of excavation

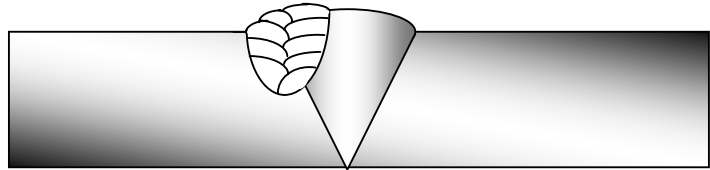
At this stage NDT should be used to confirm that the defect has been completely excavated from the area.

Re-welding of the excavation

Prior to re-welding of the excavation a detailed repair welding procedure/ method statement shall be approved.



Typical side view of weld repair



NDT confirmation of successful repair

After the excavation has been filled the weldment should then undergo a complete retest using the same NDT techniques as previously used to establish the original repair. This is carried out to ensure no further defects have been introduced by the repair welding process. NDT may also need to be further applied after any additional postweld heat treatment has been carried out.

In-service Repairs

Most in-service repairs can be of a very complex nature as the component is very likely to be in a different welding position and condition than it was during production. It may also have been in contact with toxic or combustible fluids hence a permit to work will need to be sought prior to any work being carried out. The repair welding procedure may look very different to the original production procedure due to changes in these elements.

Other factors may also be taken into consideration, such as the effect of heat on any surrounding areas of the component, ie electrical components, or materials that may become damaged by the repair procedure. This may also include difficulty in carrying out any required pre- or post-welding heat treatments and a possible restriction of access to the area to be repaired. For large fabrications it is likely that the repair must also take place on site without a shutdown of operations, which may bring other elements that need to be considered.

Repair of in-service defects may require consideration of these and many other factors, and as such are generally considered more complicated than production repairs.

Joining technologies often play a vital role in the repair and maintenance of structures. Parts can be replaced, worn or corroded parts can be built up, and cracks can be repaired.

When a repair is required it is important to determine two things: Firstly, the reason for failure and, secondly, can the component be repaired? The latter point infers that the material type is known. For metals, particularly those to be welded, the chemical composition is vitally important. Failure modes often indicate the approach required to make a sound repair. When the cause-effect analysis, however simple, is not followed through it is often the case that the repair is unsafe — sometimes disastrously so.

In many instances, the Standard or Code used to design the structure will define the type of repair that can be carried out and will also give guidance on the methods to be followed. Standards imply that when designing or manufacturing a new product it is important to consider a maintenance regime and repair procedures. Repairs may be required during manufacture and this situation should also be considered.

Normally there is more than one way of making a repair. For example, cracks in cast iron might be held together or repaired by pinning, bolting, riveting, welding, or brazing. The method chosen will depend on factors such as the reason for failure, material composition and cleanliness, environment and the size and shape of the component.

It is **very important** that repair and maintenance welding are not regarded as activities, which are simple or straightforward. In many instances a repair

may seem undemanding but the consequences of getting it wrong can be catastrophic failure with disastrous consequences.

Is welding the best method of repair?

If repair is called for because a component has a local irregularity or a shallow defect, grinding out any defects and blending to a smooth contour might be acceptable. It will certainly be preferable if the steel has poor weldability or if fatigue loading is severe. It is often better to reduce the so-called factor of safety slightly, than to risk putting defects, stress concentrations and residual stresses into a brittle material.

In fact brittle materials – which can include some steels (particularly in thick sections) as well as cast irons – may not be able to withstand the residual stresses imposed by heavy weld repairs, particularly if defects are not all removed, leaving stress concentrations to initiate cracking.

Is the repair like earlier repairs?

Repairs of one sort may have been routine for years, but it is important to check that the next one is not subtly different. For example, the section thickness may be greater; the steel to be repaired may be different and less weldable, or the restraint higher. If there is any doubt, answer the remaining questions.

What is the composition and weldability of the base metal?

The original drawings will usually give some idea of the steel involved, although the specification limits may then have been less stringent, and the specification may not give enough compositional details to be helpful. If sulphur-bearing free-machining steel is involved, it could give hot cracking problems during welding.

If there is any doubt about the composition, a chemical analysis should be carried out. It is important to analyse for all elements, which may affect weldability (Ni, Cr, Mo, Cu, V, Nb and B) as well as those usually, specified (C, S, P, Si and Mn).

A small cost spent on analysis could prevent a valuable component being ruined by ill-prepared repairs or, save money by reducing or avoiding the need for preheat if the composition were leaner than expected. Once the composition is known, a welding procedure can be devised.

What strength is required from the repair?

The higher the yield strength of the repair weld metal, the greater the residual stress level on completion of welding, risk of cracking, clamping needed to avoid distortion and more difficulty in formulating the welding procedure. In any case, the practical limit for the yield strength of conventional steel weld metals is about 1000N/mm^2 .

Can preheat be tolerated?

Not only does a high level of preheat make conditions more difficult for the welder; the parent steel can be damaged if it has been tempered at a low temperature. In other cases the steel being repaired may contain items which are damaged by excessive heating. Preheat levels can be reduced by using consumables of ultra-low hydrogen content or by non-ferritic weld metals. Of these, austenitic electrodes may need some preheat, but the more expensive nickel alloys usually do not. However, the latter may be sensitive to high sulphur and phosphorus contents in the parent steel if diluted into the weld metal.

Can softening or hardening of the HAZ be tolerated?

Softening of the HAZ is likely in very high strength steels, particularly if they have been tempered at low temperatures. Such softening cannot be avoided, but its extent can be minimised. Hard HAZs are particularly vulnerable where service conditions can lead to stress corrosion. Solutions containing H₂S (hydrogen sulphide) may demand hardness below 248HV (22HRC) although fresh aerated seawater appears to tolerate up to about 450HV. Excessively hard HAZs may, therefore, require PWHT to soften them but provided cracking has been avoided.

Is PWHT practicable?

Although it may be desirable, PWHT may not be possible for the same reasons that preheating is not. For large structures, local PWHT may be possible, but care should be taken to abide by the relevant codes, because it is too easy to introduce new residual stresses by improperly executed PWHT.

Is PWHT necessary?

PWHT may be needed for one of several reasons, and the reason must be known before considering whether it can be avoided.

Will the fatigue resistance of the repair be adequate?

If the repair is in an area which is highly stressed by fatigue and particularly if the attempted repair is of a fatigue crack, inferior fatigue life can be expected unless the weld surface is ground smooth and no surface defects are left. Fillet welds, in which the root cannot be ground smooth, are not tolerable in areas of high fatigue stress.

Will the repair resist its environment?

Besides corrosion, it is important to consider the possibility of stress corrosion, corrosion fatigue, thermal fatigue and oxidation in-service.

Corrosion and oxidation resistance usually require the composition of the filler metal is at least as noble or oxidation resistant as the parent metal. For corrosion fatigue resistance, the repair weld profile may need to be smoothed.

To resist stress corrosion, PWHT may be necessary to restore the correct microstructure, reduce hardness and the residual stress left by the repair.

Can the repair be inspected and tested?

For onerous service, radiography and/or ultrasonic examination are often desirable, but problems are likely if stainless steel or nickel alloy filler is used; moreover, such repairs cannot be assessed by MPI. In such cases, it is particularly important to carry out the procedural tests for repairs very critically, to ensure there are no risks of cracking and no likelihood of serious welder-induced defects.

Indeed, for all repair welds, it is vital to ensure that the welders are properly motivated and carefully supervised.

As-welded repairs

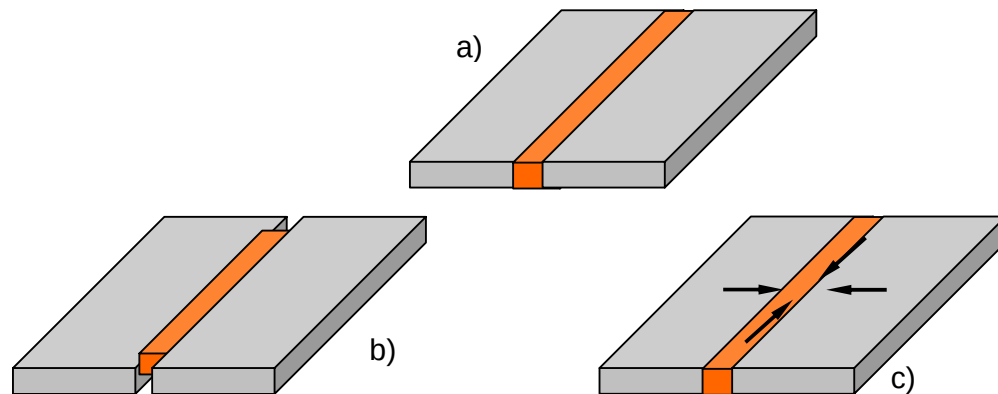
Repair without PWHT is, of course, normal where the original weld was not heat treated, but some alloy steels and many thick-sectioned components require PWHT to maintain a reasonable level of toughness, corrosion resistance, etc. However, PWHT of components in-service is not always easy or even possible, and local PWHT may give rise to more problems than it solves except in simple structures.

1 Residual Stresses and Distortions

1.1 Development of residual stresses

Because welding involves highly localised heating of joint edges to fuse the material, non-uniform stresses are set up in the components being joined. These stresses are generated because of expansion and contraction of the heated material. Initially, compressive stresses are created in the surrounding cold parent metal when the weld pool is formed due to the thermal expansion of the hot metal (heat affected zone (HAZ)) adjacent to the weld pool. However, tensile stresses occur on cooling when the contraction of the weld metal and the immediate HAZ is resisted by the bulk of the cold parent metal.

As long as these stresses are above the yield point of the metal at the prevailing temperature, they continue to produce permanent deformation, but in so doing they are relieved and fall to yield-stress level. They then cease to cause further distortion. But, if at this point we could release the weld from the plate by cutting along the joint line, it would shrink further because, even when distortion has stopped, the weld contains an elastic strain equivalent to the yield stress. Visualise the completed joint as an element of weld metal being stretched elastically between two plates.



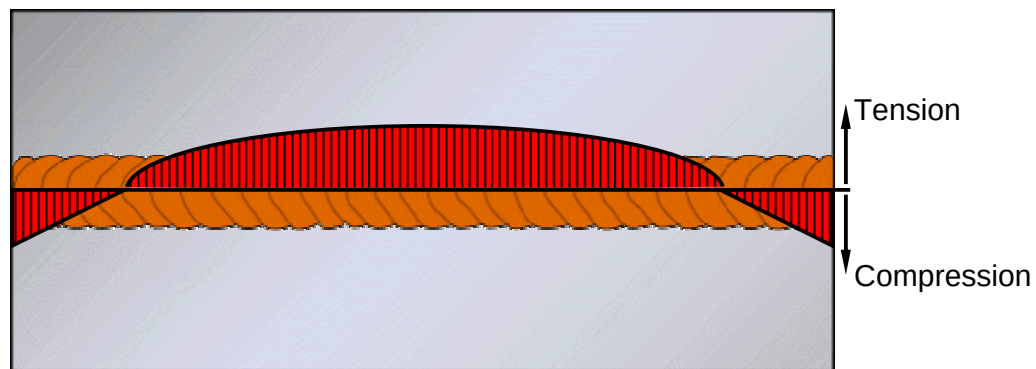
Shrinkage of a weld metal element during cooling: a) The weld is hot on its entire length and starts to cool; b) If unfused to the parent metal, the weld will shrink, reducing its dimensions on all three directions; c) Since the weld is fused to the parent metal, under combined cooling residual stresses will occur.

The stresses left in the joint after welding are referred to as residual stresses. From the above sketch, it can be seen that there will be both longitudinal and transverse stresses (in the case of a very thick plate, there is a through-thickness component of residual stress as well).

1.2 Distribution of residual stresses

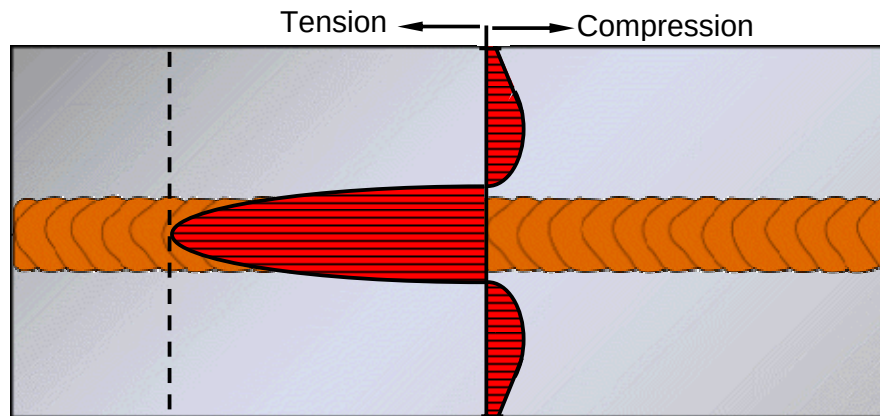
The magnitude of thermal stresses induced into the material can be seen by the volume change in the weld area on solidification and subsequent cooling to room temperature. For example, when welding C-Mn steel, the molten weld metal volume will be reduced by approximately 3% on solidification and the volume of the solidified weld metal/ HAZ will be reduced by a further 7% as its temperature falls from the melting point of steel to room temperature.

Perpendicular to the weld, in the transverse direction, the stresses in the weld are more dependent on the clamping condition of the parts. The transverse residual stresses are often relatively small, although transverse distortion is substantial. The distribution of transverse residual stresses in a butt joint is shown below. Tensile stress of a relatively low magnitude is produced in the middle section of the joint, while compressive stress is generated at both ends of the joint. It must be noted that the longer the weld, the higher would be the tensile residual stress until the yield stress is reached.



The pattern of residual stresses on transverse direction

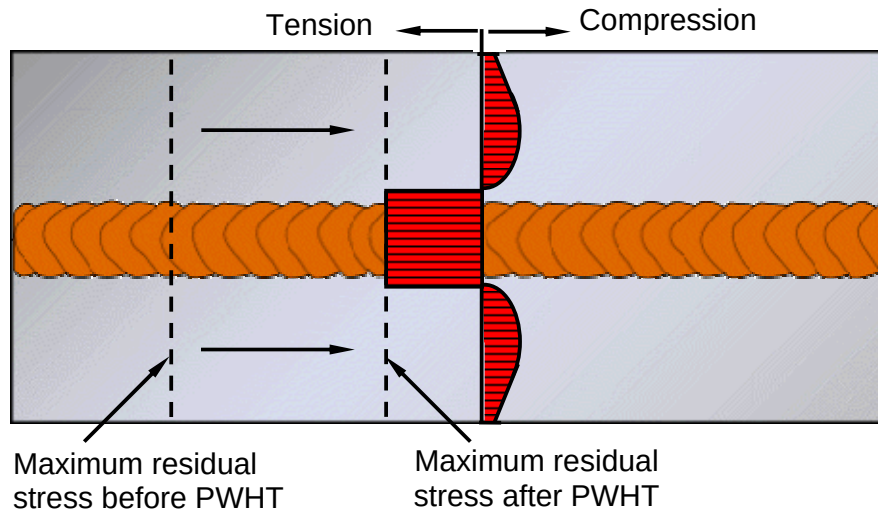
In the case of the longitudinal stresses, the weld itself and some of the plate which has been heated are at or near yield-stress level. Moving out into the plate from the HAZ, the stresses first fall to zero (please note that tensile stress region extends beyond the weld and HAZ into the parent plate!). Beyond this there is a region of compressive stress. Note that the width of the band where tensile residual stresses are present depends upon the heat input during welding – the higher the heat input the wider the band where these tensile residual stresses do occur.



The pattern of residual stresses on longitudinal direction in the as-welded conditions (the maximum level of tensile residual stress is equal to the value of the yield strength of the weld metal at room temperature).

It must be emphasised that all fusion welds which have not been subjected to post-weld treatments – in other words, the vast majority of welded joints – contain residual stresses. Procedures developed to minimise distortion may well alter the distribution of the residual stresses but do not eliminate them or even reduce their peak level.

One method of reducing the level of residual stress in a welded joint is to perform a post-weld heat treatment (PWHT) to relieve these stresses. In this case, once the temperature is raised up, the yield stress starts to drop. As a result of this phenomenon, the peak residual stresses, which were up to the value of yield stress at room temperature, cannot be carried over anymore by the material and are relaxed by plastic deformation (usually, this plastic deformation is confined at the level of grains but in some situations it can lead to significant deformation of the welded component). This process ends when the material has reached the soaking temperature. Consequently, the level of residual stresses will be reduced by the difference between the value of the yield stress at room temperature (at the beginning of PWHT) and the value of the yield stress at the soaking temperature. As it can be seen from the following sketch, this can reduce the level of tensile residual stresses up to a quarter of its initial level. However, compressive residual stresses are left unchanged. It must be pointed out that PWHT does not completely eliminate these residual stresses!



The pattern of residual stresses on longitudinal direction after PWHT.

1.3 The effect of residual stresses

Since we cannot avoid the formation of residual stresses, it is appropriate to ask if we are worried by their presence. As with so many engineering situations the answer is not a simple yes or no. There are numerous applications where the existence of residual stresses would have little or no influence on the service behaviour of the joint – storage tanks, building frames, low pressure pipework and domestic equipment all provide examples of situations where the joints can be used in the as-welded condition without detriment.

Residual stresses are considered detrimental because they:

- Lead to distortion. A distorted, out-of-shape welded structure cannot be fitted anymore for the purpose it has been manufactured.
- **Affect dimensional stability of the welded assembly. When machining welded components, removing layers of metal near the joint may disturb the balance between the tensile and compressive residual stresses and further deformation or warping can occur. This can make it difficult to hold critical machining tolerances and it may be desirable in these circumstances to stress-relieve to achieve dimensional stability.**
- Enhance the risk of brittle fracture. When residual stresses are present in a welded component, there is need only for a small extra stress added to these residual stresses to initiate a brittle fracture, providing other conditions are also met (ie low temperature).

- They can facilitate certain types of corrosion. Some metals in certain environments corrode rapidly in the presence of tensile stress, ie stress corrosion cracking will occur. In these cases, a joint in the as-welded condition containing residual stresses suffers excessive attack; this is retarded if the joint is stress-relieved.

If the service requirements do indicate that the residual stresses are undesirable, the designer must take them into account when selecting materials and deciding upon a safe working stress. This approach can be seen in the design of ships, where the combination of low temperatures and residual stress could lead to brittle fracture. The designer selects a material, which is not susceptible to this mode of failure even at the low temperatures, which may be experienced during the working life of the ship; the presence of residual stresses is then not important. Similarly, in many structures subjected to loads which fluctuate during service – for example, bridges, earth-moving equipment and cranes – the designer recognises the existence of residual stresses by choosing a working stress range which takes account of the role these stresses play in the formation and propagation of fatigue cracks. There are, however, some specific applications where it is essential to reduce the level of residual stresses in the welded joint. With pressure vessels, because of the risk of a catastrophic failure by brittle fracture, stress relieving is often a statutory or insurance requirement.

1.4 Factors affecting residual stresses

Factors affecting residual stresses in a welded joint can be grouped into 5 categories:

1. Material properties
2. Amount of restraint
3. Joint design
4. Fit-up
5. Welding sequence

2 What Causes Distortion?

Because welding involves highly localised heating of joint edges to fuse the material, non-uniform stresses are set up in the component because of expansion and contraction of the heated material.

Initially, compressive stresses are created in the surrounding cold parent metal when the weld pool is formed due to the thermal expansion of the hot metal (HAZ) adjacent to the weld pool. However, tensile stresses occur on cooling when the contraction of the weld metal and immediate HAZ is resisted by the bulk of the cold parent metal.

The magnitude of thermal stresses induced into the material can be seen by the volume change in the weld area on solidification and subsequent cooling to room temperature. For example, when welding C-Mn steel, the molten weld metal volume will be reduced by approximately 3% on solidification and the volume of the solidified weld metal/HAZ will be reduced by a further 7% as its temperature falls from the melting point of steel to room temperature.

If the stresses generated from thermal expansion/contraction exceed the yield strength of the parent metal, localised plastic deformation of the metal occurs. Plastic deformation causes a permanent reduction in the component dimensions and distorts the structure.

3 What Are the Main Types of Distortion?

Distortion occurs in several ways:

- Longitudinal shrinkage.
- Transverse shrinkage.
- Angular distortion.
- Bowing and dishing.
- Buckling.

Contraction of the weld area on cooling results in both **transverse** and **longitudinal** shrinkage.

Non-uniform contraction (through-thickness) produces **angular** distortion as well as longitudinal and transverse shrinking.

For example, in a single V butt weld, the first weld run produces longitudinal and transverse shrinkage and rotation. The second run causes the plates to rotate using the first weld deposit as a fulcrum. Therefore, balanced welding in a double-sided V butt joint can be used to produce uniform contraction and prevent angular distortion.

Similarly, in a single-sided fillet weld, non-uniform contraction will produce angular distortion of the upstanding leg. Double-sided fillet welds can therefore be used to control distortion in the upstanding fillet but because the weld is only deposited on one side of the base plate, angular distortion will now be produced in the plate.

Longitudinal **bowing** in welded plates happens when the weld centre is not coincident with the neutral axis of the section so that longitudinal shrinkage in the welds bends the section into a curved shape. Clad plate tends to bow in two directions due to longitudinal and transverse shrinkage of the cladding. This produces a dished shape.

Dishing is also produced in stiffened plating. Plates usually dish inwards between the stiffeners, because of angular distortion at the stiffener attachment welds.

In plating, long range compressive stresses can cause elastic buckling in thin plates, resulting in dishing, bowing or rippling. see Figure 1.

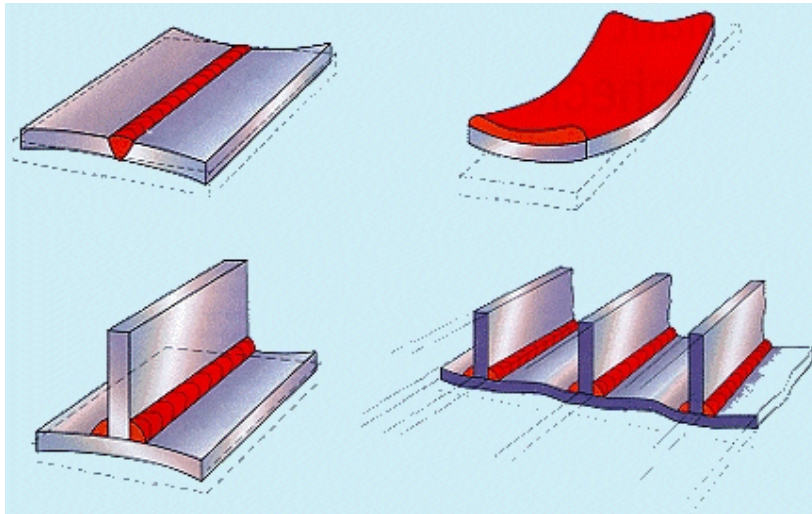


Figure 1 Examples of distortion.

Increasing the leg length of fillet welds, in particular, increases shrinkage.

4 What Are the Factors Affecting Distortion?

If a metal is uniformly heated and cooled there would be almost no distortion. However, because the material is locally heated and restrained by the surrounding cold metal, stresses are generated higher than the material yield stress causing permanent distortion. The principal factors affecting the type and degree of distortion are:

- Parent material properties.
- Amount of restraint.
- Joint design.
- Part fit-up.
- Welding procedure.

4.1 Parent material properties

Parent material properties, which influence distortion, are coefficient of thermal expansion, thermal conductivity, and to a lesser extent, yield stress and Young's modulus. As distortion is determined by expansion and contraction of the material, the coefficient of thermal expansion of the material plays a significant role in determining the stresses generated during welding and, hence, the degree of distortion. For example, as stainless steel has a higher coefficient of expansion and lesser thermal conductivity than plain carbon steel, it generally has significantly more distortion.

4.2 Restraint

If a component is welded without any external restraint, it distorts to relieve the welding stresses. So, methods of restraint, such as strongbacks in butt welds, can prevent movement and reduce distortion. As restraint produces higher levels of residual stress in the material, there is a greater risk of cracking in weld metal and HAZ especially in crack-sensitive materials.

4.3 Joint design

Both butt and fillet joints are prone to distortion. It can be minimised in butt joints by adopting a joint type which balances the thermal stresses through the plate thickness. For example, double-sided in preference to a single-sided weld. Double-sided fillet welds should eliminate angular distortion of the upstanding member, especially if the two welds are deposited at the same time.

4.4 Part fit-up

Fit-up should be uniform to produce predictable and consistent shrinkage. Excessive joint gap can also increase the degree of distortion by increasing the amount of weld metal needed to fill the joint. The joints should be adequately tacked to prevent relative movement between the parts during welding.

4.5 Welding procedure

This influences the degree of distortion mainly through its effect on the heat input. As welding procedures are usually selected for reasons of quality and productivity, the welder has limited scope for reducing distortion. As a general rule, weld volume should be kept to a minimum. Also, the welding sequence and technique should aim to balance the thermally induced stresses around the neutral axis of the component.

5 Distortion – Prevention by Pre-Setting, Pre-Bending or Use of Restraint

Distortion can often be prevented at the design stage, for example, by placing the welds about the neutral axis, reducing the amount of welding and depositing the weld metal using a balanced welding technique. In designs where this is not possible, distortion may be prevented by one of the following methods:

- Pre-setting of parts.
- Pre-bending of parts.
- Use of restraint.

The technique chosen will be influenced by the size and complexity of the component or assembly, the cost of any restraining equipment and the need to limit residual stresses.

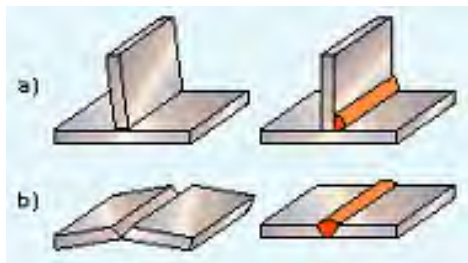


Figure 2 Pre-setting of parts to produce correct alignment after welding:

- a) Fillet joint to prevent angular distortion
b) Butt joint to prevent angular distortion

5.1 Pre-setting of parts

The parts are pre-set and left free to move during welding, see Figure 2. In practice, the parts are pre-set by a pre-determined amount so that distortion occurring during welding is used to achieve overall alignment and dimensional control.

The main advantages compared with the use of restraint are that there is no expensive equipment needed and there will be lower residual stress in the structure.

Unfortunately, as it is difficult to predict the amount of pre-setting needed to accommodate shrinkage, a number of trial welds will be required. For example, when MMA or MIG/MAG welding butt joints, the joint gap will normally close ahead of welding; when SAW the joint may open up during welding. When carrying out trial welds, it is also essential that the test structure is reasonably representative of the full size structure in order to generate the level of distortion likely to occur in practice. For these reasons, pre-setting is a technique more suitable for simple components or assemblies.

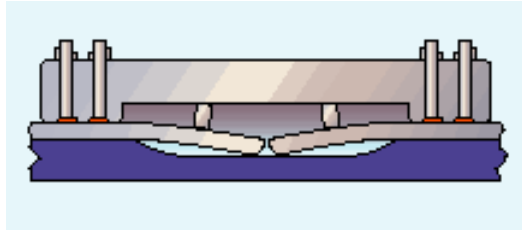


Figure 3 Pre-bending, using strongbacks and wedges, to accommodate angular distortion in thin plates.

5.2 Pre-bending of parts

Pre-bending or pre-springing the parts before welding is a technique used to pre-stress the assembly to counteract shrinkage during welding. As shown in Figure 3, pre-bending by means of strongbacks and wedges can be used to pre-set a seam before welding to compensate for angular distortion. Releasing the wedges after welding will allow the parts to move back into alignment.

The main photograph shows the diagonal bracings and centre jack used to pre-bend the fixture, not the component. This counteracts the distortion introduced through out-of-balance welding.

5.3 Use of restraint

Because of the difficulty in applying pre-setting and pre-bending, restraint is the more widely practised technique. The basic principle is that the parts are placed in position and held under restraint to minimise any movement during welding. When removing the component from the restraining equipment, a relatively small amount of movement will occur due to locked-in stresses. This can be cured by either applying a small amount of pre-set or stress-relieving before removing the restraint.

When welding assemblies, all the component parts should be held in the correct position until completion of welding and a suitably balanced fabrication sequence used to minimise distortion.

Welding with restraint will generate additional residual stresses in the weld, which may cause cracking. When welding susceptible materials, a suitable welding sequence and the use of preheating will reduce this risk.

Restraint is relatively simple to apply using clamps, jigs and fixtures to hold the parts during welding.

5.3.1 Welding jigs and fixtures

Jigs and fixtures are used to locate the parts and to ensure that dimensional accuracy is maintained whilst welding. They can be of a relatively simple construction, as shown in Figure 4a but the welding engineer will need to ensure that the finished fabrication can be removed easily after welding.

5.3.2 Flexible clamps

A flexible clamp (Figure 4b) can be effective not only in applying restraint but also in setting up and maintaining the joint gap (it can also be used to close a gap that is too wide).

A disadvantage is that as the restraining forces in the clamp will be transferred into the joint when the clamps are removed, the level of residual stress across the joint can be quite high.

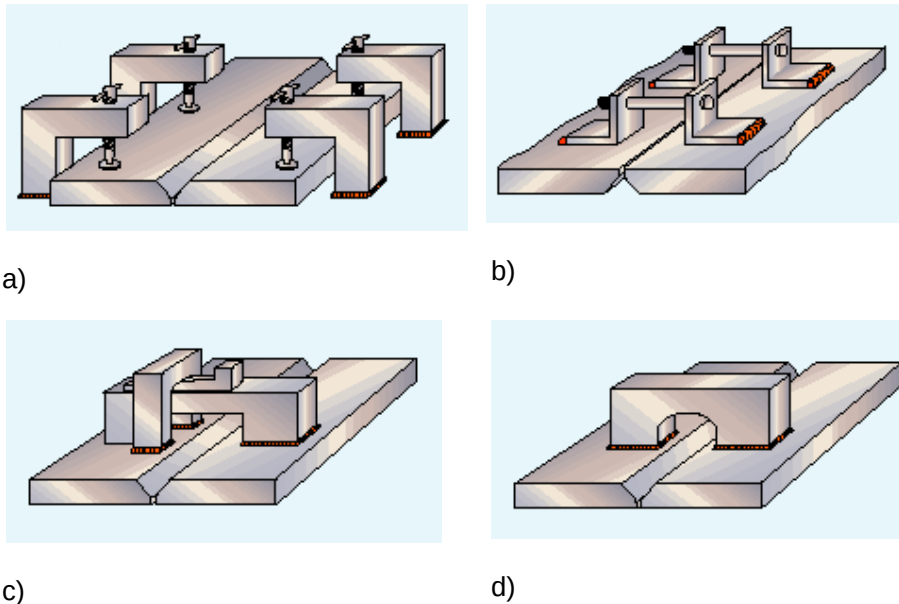


Figure 4 Restraint techniques to prevent distortion:

- a) Welding jig;
- b) Flexible clamps;
- c) Strongbacks with wedges;
- d) Fully wedged strongbacks.

5.3.3 Strongbacks (and wedges)

Strongbacks are a popular means of applying restraint especially for site work. Wedged strongbacks (Figure 4c), will prevent angular distortion in plate and help to prevent peaking in welding cylindrical shells. As these types of strongback will allow transverse shrinkage, the risk of cracking will be greatly reduced compared with fully welded strongbacks.

Fully welded (welded on both sides of the joint) strongbacks (Figure 4d) will minimise both angular distortion and transverse shrinkage. As significant stresses can be generated across the weld, which will increase any tendency for cracking, care should be taken in the use of this type of strongback.

5.4 Best practice

Adopting the following assembly techniques will help to control distortion:

- Pre-set parts so that welding distortion will achieve overall alignment and dimensional control with the minimum of residual stress.
- Pre-bend joint edges to counteract distortion and achieve alignment and dimensional control with minimum residual stress.
- Apply restraint during welding by using jigs and fixtures, flexible clamps, strongbacks and tack welding but consider the risk of cracking which can be quite significant, especially for fully welded strongbacks.
- Use an approved procedure for welding and removal of welds for restraint techniques, which may need preheat to avoid forming imperfections in the component surface.

6 Distortion – Prevention by Design

Design principles

At the design stage, welding distortion can often be prevented, or at least restricted, by considering:

- Elimination of welding.
- Weld placement.
- Reducing the volume of weld metal.
- Reducing the number of runs.
- Use of balanced welding.

6.1 Elimination of welding

As distortion and shrinkage are an inevitable result of welding, good design requires that not only the amount of welding is kept to a minimum, but also the smallest amount of weld metal is deposited. Welding can often be eliminated at the design stage by forming the plate or using a standard rolled section, as shown in Figure 5.

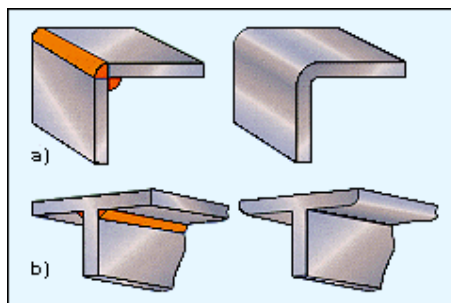


Figure 5 Elimination of welds by
a) Forming the plate;
b) Use of rolled or extruded section.

If possible, the design should use intermittent welds rather than a continuous run, to reduce the amount of welding. For example, in attaching stiffening plates, a substantial reduction in the amount of welding can often be achieved whilst maintaining adequate strength.

6.2 Weld placement

Placing and balancing of welds are important in designing for minimum distortion. The closer a weld is positioned to the neutral axis of a fabrication, the lower the leverage effect of the shrinkage forces and the final distortion. Examples of poor and good designs are shown below (Figure 6).

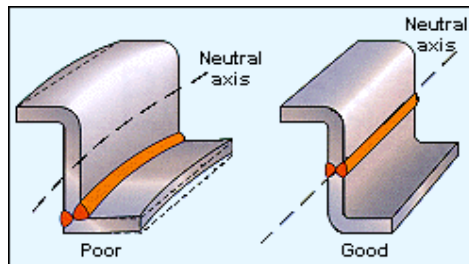


Figure 6 Distortion may be reduced by placing the welds around the neutral axis.

As most welds are deposited away from the neutral axis, distortion can be minimised by designing the fabrication so the shrinkage forces of an individual weld are balanced by placing another weld on the opposite side of the neutral axis. Whenever possible, welding should be carried out alternately on opposite sides, instead of completing one side first. In large structures, if distortion is occurring preferentially on one side, it may be possible to take corrective action, for example, by increasing welding on the other side to control the overall distortion.

6.3 Reducing the volume of weld metal

To minimise distortion, as well as for economic reasons, the volume of weld metal should be limited to the design requirements. For a single-sided joint, the cross-section of the weld should be kept as small as possible to reduce the level of angular distortion, as illustrated in Figure 7.

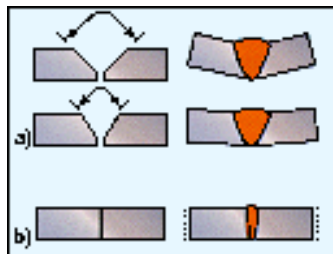


Figure 7 Reducing the amount of angular distortion and lateral shrinkage.

Ways of reducing angular distortion and lateral shrinkage:

- Reducing the volume of weld metal.
- Using single pass weld.
- Ensure fillet welds are not oversize.

Joint preparation angle and root gap should be minimised providing the weld can be made satisfactorily. To facilitate access, it may be possible to specify a larger root gap and smaller preparation angle. By reducing the difference in the amount of weld metal at the root and the face of the weld, the degree of angular distortion will be correspondingly reduced. Butt joints made in a single pass using deep penetration have little angular distortion, especially if a closed butt joint can be welded (Figure 7). For example, thin section material can be welded using plasma and laser welding processes and thick section can be welded, in the vertical position, using electrogas and electroslag processes. Although angular distortion can be eliminated, there will still be longitudinal and transverse shrinkage.

In thick section material, as the cross-sectional area of a double V joint preparation is often only half that of a single V, the volume of weld metal to be deposited can be substantially reduced. The double V joint preparation also permits balanced welding about the middle of the joint to eliminate angular distortion.

As weld shrinkage is proportional to the amount of weld metal both poor joint fit-up and over-welding will increase the amount of distortion. Angular distortion in fillet welds is particularly affected by over-welding. As design strength is based on throat thickness, over-welding to produce a convex weld bead does not increase the allowable design strength but it will increase the shrinkage and distortion.

6.4 Reducing the number of runs

There are conflicting opinions on whether it is better to deposit a given volume of weld metal using a small number of large weld passes or a large number of small passes. Experience shows that for a single-sided butt joint, or fillet weld, a large single weld deposit gives less angular distortion than if the weld is made with a number of small runs. Generally, in an unrestrained joint, the degree of angular distortion is approximately proportional to the number of passes.

Completing the joint with a small number of large weld deposits results in more longitudinal and transverse shrinkage than a weld completed in a larger number of small passes. In a multi-pass weld, previously deposited weld metal provides restraint, so the angular distortion per pass decreases as the weld is built up. Large deposits also increase the risk of elastic buckling particularly in thin section plate.

6.5 Use of balanced welding

Balanced welding is an effective means of controlling angular distortion in a multi-pass butt weld by arranging the welding sequence to ensure that angular distortion is continually being corrected and not allowed to accumulate during welding. Comparative amounts of angular distortion from balanced welding and welding one side of the joint first are shown in this figure. The balanced welding technique can also be applied to fillet joints.

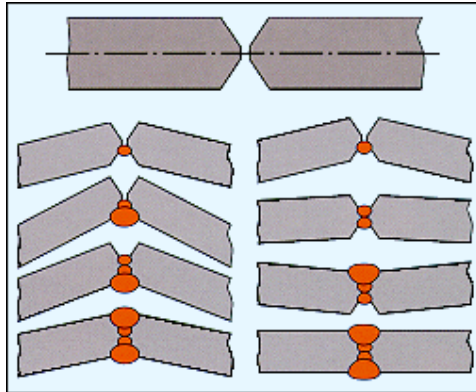


Figure 8 *Balanced welding to reduce the amount of angular distortion.*

If welding alternately on either side of the joint is not possible, or if one side has to be completed first, an asymmetrical joint preparation may be used with more weld metal being deposited on the second side. The greater contraction resulting from depositing the weld metal on the second side will help counteract the distortion on the first side.

6.6 Best practice

The following design principles can control distortion:

- Eliminate welding by forming the plate and using rolled or extruded sections.
- Minimise the amount of weld metal.
- Do not over-weld.
- Use intermittent welding in preference to a continuous weld pass.
- Place welds about the neutral axis.
- Balance the welding about the middle of the joint by using a double V in preference to a single V joint.

Adopting best practice principles can have surprising cost benefits. For example, for a design fillet leg length of 6mm, depositing an 8mm leg length will result in the deposition of 57% additional weld metal. Besides the extra cost of depositing weld metal and the increase risk of distortion, it is costly to remove this extra weld metal later. However, designing for distortion control may incur additional fabrication costs. For example, the use of a double V joint preparation is an excellent way to reduce weld volume and control distortion, but extra costs may be incurred in production through manipulation of the workpiece for the welder to access the reverse side.

7 Distortion – Prevention by Fabrication Techniques

7.1 Assembly techniques

In general, the welder has little influence on the choice of welding procedure but assembly techniques can often be crucial in minimising distortion. The principal assembly techniques are:

- Tack welding.
- Back-to-back assembly.
- Stiffening.

7.1.1 Tack welding

Tack welds are ideal for setting and maintaining the joint gap but can also be used to resist transverse shrinkage. To be effective, thought should be given to the number of tack welds, their length and the distance between them. With too few, there is the risk of the joint progressively closing up as welding proceeds. In a long seam, using MMA or MIG/MAG, the joint edges may even overlap. It should be noted that when using the submerged arc process, the joint might open up if not adequately tacked.

The tack welding sequence is important to maintain a uniform root gap along the length of the joint. Three alternative tack welding sequences are shown:

- Straight through to the end of the joint (Figure 9a). It is necessary to clamp the plates or to use wedges to maintain the joint gap during tacking.
- One end and then use a back stepping technique for tacking the rest of the joint (Figure 9b).
- Centre and complete the tack welding by back stepping (Figure 9c).

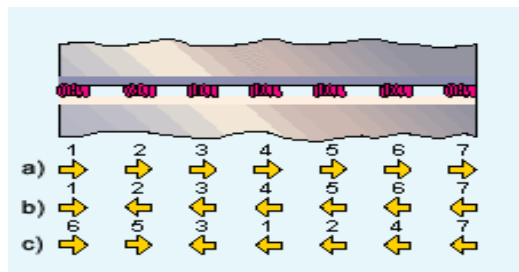


Figure 9 Alternative procedures used for tack welding to prevent transverse shrinkage.

Directional tacking is a useful technique for controlling the joint gap, for example closing a joint gap which is (or has become) too wide.

When tack welding, it is important that tacks which are to be fused into the main weld, are produced to an approved procedure using appropriately qualified welders. The procedure may require preheat and an approved consumable as specified for the main weld. Removal of the tacks also needs careful control to avoid causing defects in the component surface.

7.1.2 Back-to-back assembly

By tack welding or clamping two identical components back-to-back, welding of both components can be balanced around the neutral axis of the combined assembly (see Figure 10a). It is recommended that the assembly is stress-relieved before separating the components. If stress-relieving is not done, it may be necessary to insert wedges between the components (Figure 10b) so when the wedges are removed, the parts will move back to the correct shape or alignment.

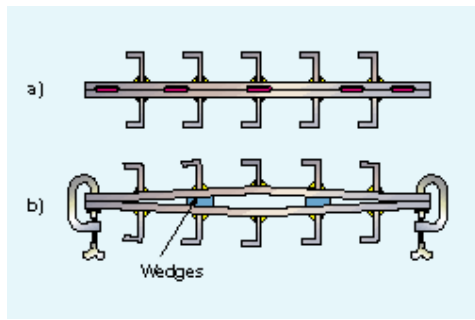


Figure 10 Back-to-back assembly to control distortion when welding two identical components:

- a) Assemblies tacked together before welding;
- b) Use of wedges for components that distort on separation after welding.

7.1.3 Stiffening

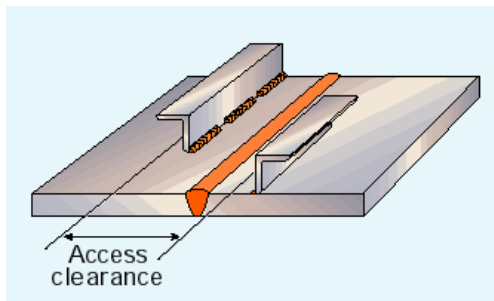


Figure 11 Longitudinal stiffeners prevent bowing in butt welded thin plate joints.

Longitudinal shrinkage in butt welded seams often results in bowing, especially when fabricating thin plate structures. Longitudinal stiffeners in the form of flats or angles, welded along each side of the seam (Figure 11) are effective in preventing longitudinal bowing. Stiffener location is important unless located on the reverse side of a joint welded from one side: they must be placed at a sufficient distance from the joint so they do not interfere with welding,

7.2 Welding procedure

A suitable welding procedure is usually determined by productivity and quality requirements rather than the need to control distortion. Nevertheless, the welding process, technique and sequence do influence the distortion level.

Welding process

General rules for selecting a welding process to prevent angular distortion are:

- Deposit the weld metal as quickly as possible.
- Use the least number of runs to fill the joint.

Unfortunately, selecting a suitable welding process based on these rules may increase longitudinal shrinkage resulting in bowing and buckling.

In manual welding, MIG/MAG, a high deposition rate process, is preferred to MMA. Weld metal should be deposited using the largest diameter electrode (MMA), or the highest current level (MIG/MAG), without causing lack-of-fusion imperfections. As heating is much slower and more diffuse, gas welding normally produces more angular distortion than the arc processes.

Mechanised techniques combining high deposition rates and high welding speeds have the greatest potential for preventing distortion. As the distortion is more consistent, simple techniques such as pre-setting are more effective in controlling angular distortion.

Welding technique

General rules for preventing distortion are:

- Keep the weld (fillet) to the minimum specified size.
- Use balanced welding about the neutral axis.
- Keep the time between runs to a minimum.

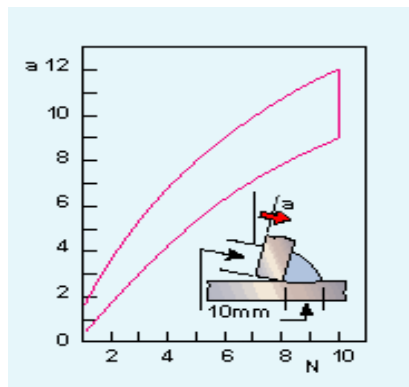


Figure 12 Angular distortion of the joint as determined by the number of runs in the fillet weld.

In the absence of restraint, angular distortion in both fillet and butt joints will be a function of joint geometry, weld size and the number of runs for a given cross-section. Angular distortion (measured in degrees) as a function of the number of runs for a 10mm leg length fillet weld is shown.

If possible, balanced welding around the neutral axis should be done, for example on double-sided fillet joints, by two people welding simultaneously. In butt joints, the run order may be crucial in that balanced welding can be used to correct angular distortion as it develops.

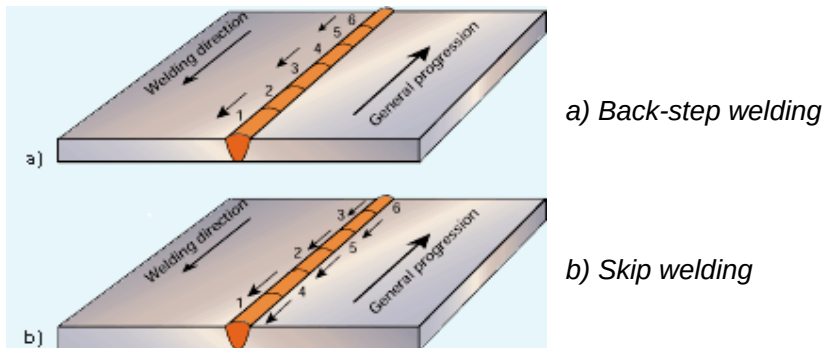


Figure 13 Use of welding direction to control distortion.

Welding sequence

The welding sequence, or direction, of welding is important and should be towards the free end of the joint. For long welds, the whole of the weld is not completed in one direction. Short runs, for example using the back-step or skip welding technique, are very effective in distortion control (Figure 13).

- Back-step welding involves depositing short adjacent weld lengths in the opposite direction to the general progression (Figure 13 a).
- Skip welding is laying short weld lengths in a predetermined, evenly spaced, sequence along the seam (Figure 13b). Weld lengths and the spaces between them are generally equal to the natural run-out length of one electrode. The direction of deposit for each electrode is the same, but it is not necessary for the welding direction to be opposite to the direction of general progression.

7.3 Best practice

The following fabrication techniques are used to control distortion:

- Using tack welds to set-up and maintain the joint gap.
- Identical components welded back-to-back so welding can be balanced about the neutral axis.
- Attachment of longitudinal stiffeners to prevent longitudinal bowing in butt welds of thin plate structures.
- Where there is a choice of welding procedure, process and technique should aim to deposit the weld metal as quickly as possible; MIG/MAG in

preference to MMA or gas welding and mechanised rather than manual welding.

- In long runs, the whole weld should not be completed in one direction; back-step or skip welding techniques should be used.

8 Distortion – Corrective Techniques

Every effort should be made to avoid distortion at the design stage and by using suitable fabrication procedures. As it is not always possible to avoid distortion during fabrication, several well-established corrective techniques can be employed. However, reworking to correct distortion should not be undertaken lightly as it is costly and needs considerable skill to avoid damaging the component.

General guidelines are provided on best practice for correcting distortion using mechanical or thermal techniques.

8.1 Mechanical techniques

The principal mechanical techniques are hammering and pressing; the hammering may cause surface damage and work hardening.

In cases of bowing or angular distortion, the complete component can often be straightened on a press without the disadvantages of hammering. Packing pieces are inserted between the component and the platens of the press. It is important to impose sufficient deformation to give over-correction so that the normal elastic spring-back will allow the component to assume its correct shape.

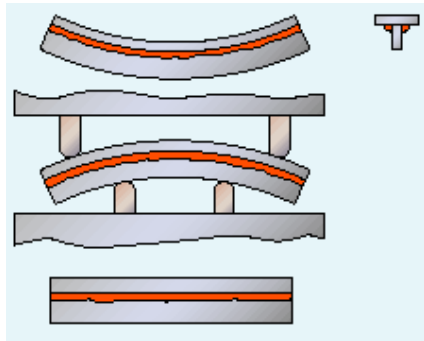


Figure 14 Use of press to correct bowing in T butt joint.

Pressing to correct bowing in flanged plate in long components, distortion is removed progressively in a series of incremental pressings; each one acting over a short length. In the case of the flanged plate, the load should act on the flange to prevent local damage to the web at the load points. As incremental point loading will only produce an approximately straight component, it is better to use a former to achieve a straight component or to produce a smooth curvature.

8.1.1 Best practice for mechanical straightening

The following should be adopted when using pressing techniques to remove distortion:

- Use packing pieces which will over-correct the distortion so that the spring-back will return the component to the correct shape.
- Check that the component is adequately supported during pressing to prevent buckling.
- Use a former (or rolling) to achieve a straight component or produce a curvature.
- As unsecured packing pieces may fly out from the press, the following safe practices must be adopted:
 - Bolt the packing pieces to the platen;
 - Place a metal plate of adequate thickness to intercept the 'missile';
 - Clear personnel from the hazard area.

8.2 Thermal techniques

The basic principle behind thermal techniques is to create sufficiently high local stresses so that, on cooling, the component is pulled back into shape.

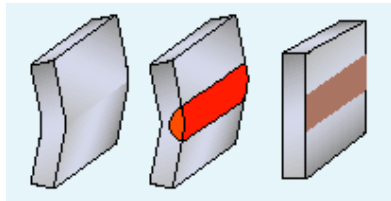


Figure 15 Localised heating to correct distortion.

This is achieved by locally heating the material to a temperature where plastic deformation will occur as the hot, low yield strength material tries to expand against the surrounding cold, higher yield strength metal. On cooling to room temperature the heated area will attempt to shrink to a smaller size than before heating. The stresses generated thereby will pull the component into the required shape, (Figure 15).

Local heating is, therefore, a relatively simple but effective means of correcting welding distortion. Shrinkage level is determined by size, number, location and temperature of the heated zones. Thickness and plate size determines the area of the heated zone. Number and placement of heating zones are largely a question of experience. For new jobs, tests will often be needed to quantify the level of shrinkage.

Spot, line, or wedge-shaped heating techniques can all be used in thermal correction of distortion.

8.2.1 Spot heating

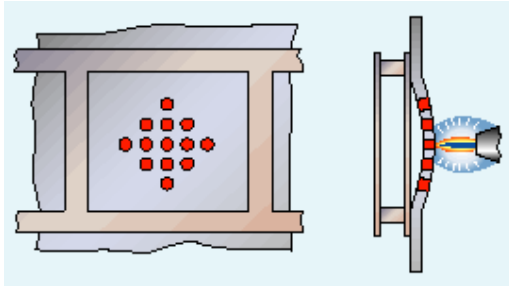


Figure 16 Spot heating for correcting buckling.

Spot heating (Figure 16), is used to remove buckling, for example when a relatively thin sheet has been welded to a stiff frame. Distortion is corrected by spot heating on the convex side. If the buckling is regular, the spots can be arranged symmetrically, starting at the centre of the buckle and working outwards.

8.2.2 Line heating

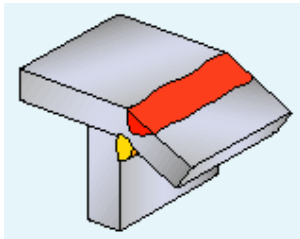


Figure 17 Line heating to correct angular distortion in a fillet weld.

Heating in straight lines is often used to correct angular distortion, for example, in fillet welds (see Figure above). The component is heated along the line of the welded joint but on the opposite side to the weld so the induced stresses will pull the flange flat.

8.2.3 Wedge-shaped heating

To correct distortion in larger complex fabrications it may be necessary to heat whole areas in addition to employing line heating. The pattern aims at shrinking one part of the fabrication to pull the material back into shape.

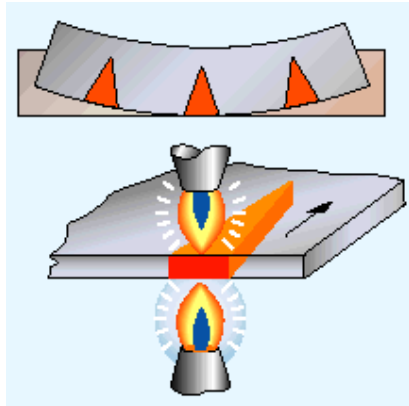


Figure 18 Use of wedge-shaped heating to straighten plate.

Apart from spot heating of thin panels, a wedge-shaped heating zone should be used, (Figure 18) from base to apex and the temperature profile should be uniform through the plate thickness. For thicker section material, it may be necessary to use two torches, one on each side of the plate.

As a general guideline, to straighten a curved plate wedge dimensions should be:

- Length of wedge - two-thirds of the plate width.
- Width of wedge (base) - one sixth of its length (base to apex).

The degree of straightening will typically be 5mm in a 3m length of plate. Wedge-shaped heating can be used to correct distortion in a variety of situations, (see Figure 19):

- Standard rolled section, which needs correction in two planes, (Figure 19a).
- Buckle at edge of plate as an alternative to rolling (Figure 19b).
- Box section fabrication, which is distorted out of plane (Figure 19c).

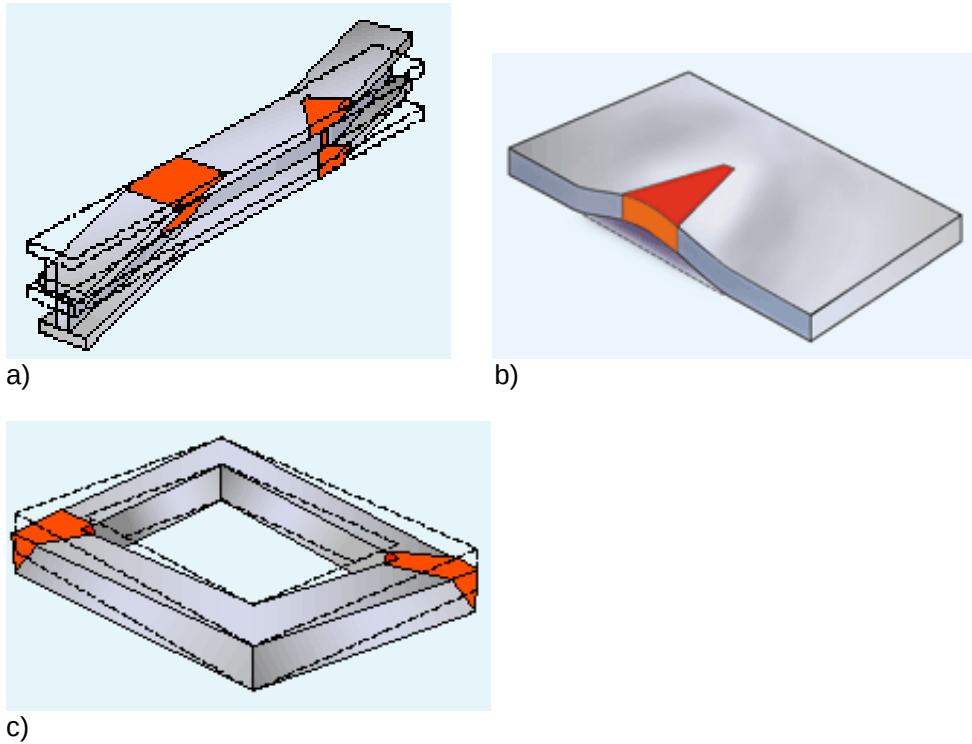


Figure 19 Wedge shaped heating to correct distortion:
a) Standard rolled steel section;
b) Buckled edge of plate;
c) Box fabrication.

8.2.4 General precautions

The dangers of using thermal straightening techniques are the risk of over-shrinking too large an area or causing metallurgical changes by heating to too high a temperature. As a general rule, when correcting distortion in steels the temperature of the area should be restricted to approximately 60-650°C – dull red heat. If the heating is interrupted, or the heat lost, the operator must allow the metal to cool and then begin again.

8.2.5 Best practice for distortion correction by thermal heating

The following should be adopted when using thermal techniques to remove distortion:

- Use spot heating to remove buckling in thin sheet structures.
- Other than in spot heating of thin panels, use a wedge-shaped heating technique.
- Use line heating to correct angular distortion in plate.
- Restrict the area of heating to avoid over-shrinking the component.
- Limit the temperature to 60-650°C (dull red heat) in steels to prevent metallurgical damage.
- In wedge heating, heat from the base to the apex of the wedge, penetrate evenly through the plate thickness and maintain an even temperature.

1 Introduction

The heat treatment given to a particular grade of steel by the steelmaker/supplier should be shown on the material test certificate and may be referred to as the supply condition.

Welding inspectors may need to refer to material test certificates and it is appropriate that they are familiar with the terminology used and have some understanding of the principles of some of the most commonly applied heat treatments.

Welded joints may need to be subjected to heat treatment after welding (PWHT) and the tasks of monitoring the thermal cycle and checking the heat treatment records are often delegated to welding inspectors.

2 Heat Treatment of Steel

The main supply conditions for weldable steels are:

As-rolled, hot rolled and hot finished

Plate is hot rolled to finished size and allowed to air cool; the temperature at which rolling finishes may vary from plate to plate and so strength and toughness properties vary and are not optimised.

Applied to

Relatively thin, lower strength C-steel.

Thermo-mechanical controlled processing (TMCP, control-rolled, thermo-mechanically rolled)

Steel plate given precisely controlled thickness reductions during hot rolling within carefully controlled temperature ranges; final rolling temperature is also carefully controlled.

Applied to

Relatively thin, high strength low alloy (HSLA) steels and some steels with good toughness at low temperatures, eg cryogenic steels.

Normalised

After working (rolling or forging) the steel to size, it is heated to ~900°C and then allowed to cool in air to ambient temperature; this optimises strength and toughness and gives uniform properties from item to item for a particular grade of steel (Figure 1).

Applied to

C-Mn steels and some low alloy steels.

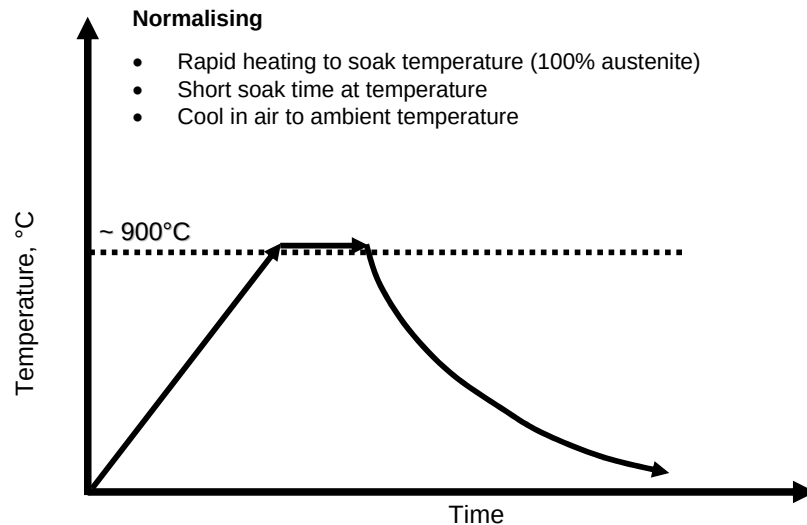


Figure 1 Typical normalising heat treatment applied to C-Mn and some low alloy steels.

Quenched and tempered

After working the steel (rolling or forging) to size, it is heated to $\sim 900^{\circ}\text{C}$ and then cooled as quickly as possible by quenching in water or oil; after quenching, the steel must be tempered (softened) to improve the ductility of the as-quenched steel (Figure 2).

Applied to

Some low alloy steels to give higher strength, toughness or wear resistance.

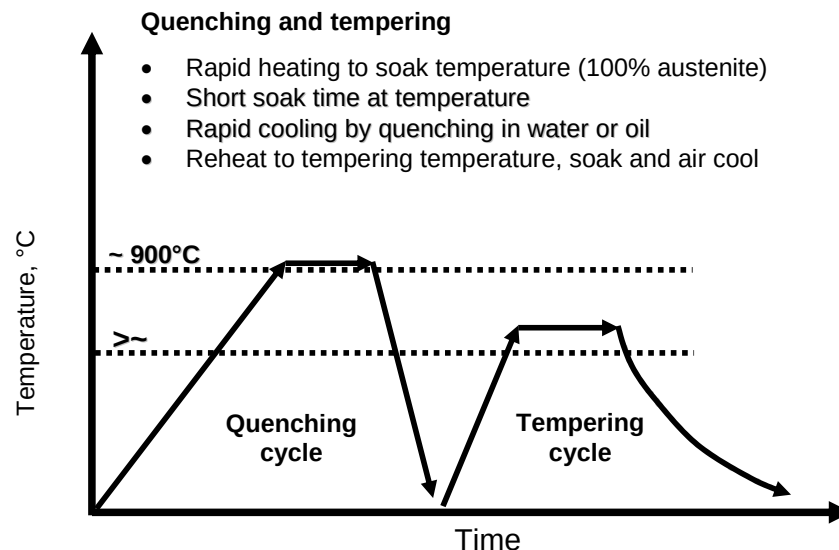


Figure 2 A typical quenching and tempering heat treatment applied to some low alloy steels.

Solution annealed

Hot or cold working to size, steel heated to $\sim 1100^{\circ}\text{C}$ after.

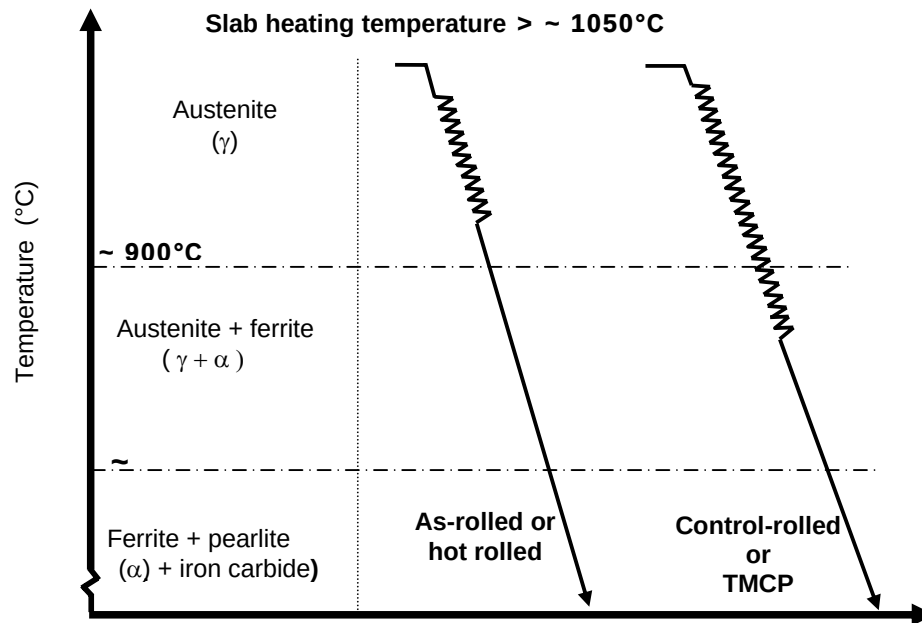


Figure 3 Comparison of the control-rolled (TMCP) and as-rolled conditions (= hot rolling)

Solution heat treated

Rapidly cooled by quenching into water to prevent any carbides or other phases forming (Figure 4).

Applied to

Austenitic stainless steels such as 304 and 316 grades.

Annealed

After working the steel (pressing or forging etc) to size, it is heated to $\sim 900^{\circ}\text{C}$, then allowed to cool in the furnace to ambient temperature; this reduces strength and toughness but improves ductility (Figure 5).

Applied to

C-Mn steels and some low alloy steels.

Figures 1-5 show thermal cycles for the main supply conditions and subsequent heat treatment that can be applied to steels.

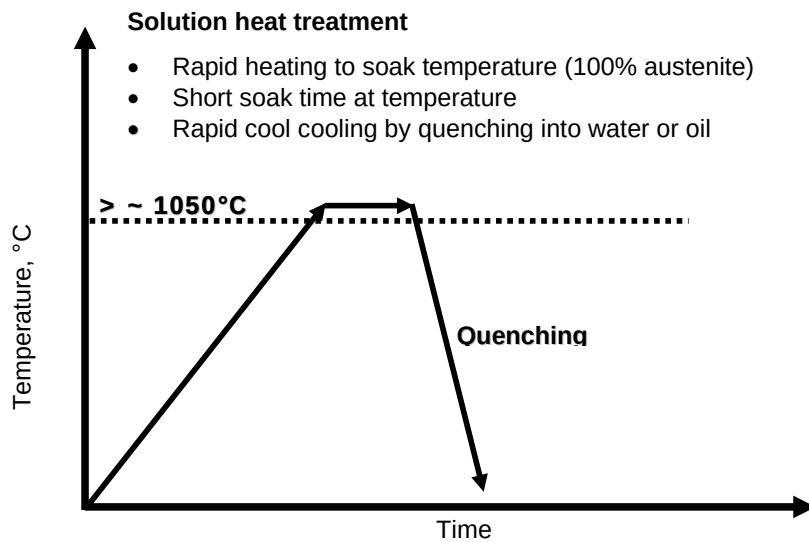


Figure 4 A typical solution heat treatment (solution annealing) applied to austenitic stainless steels

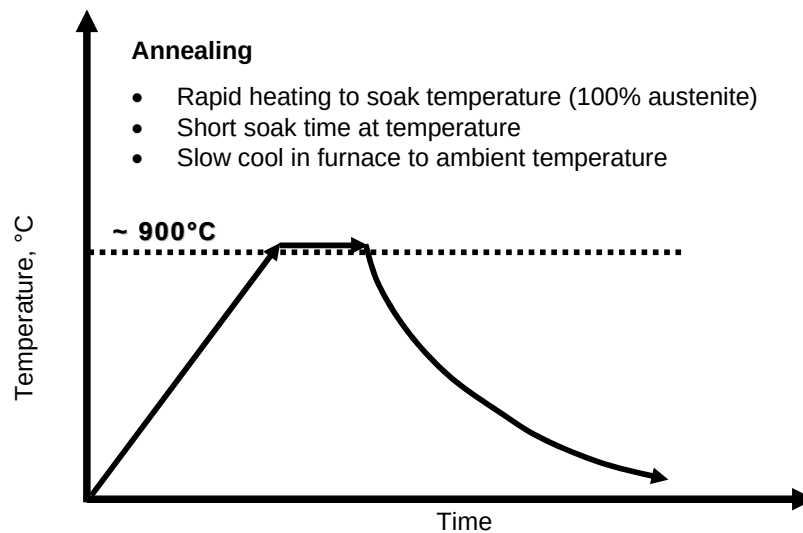


Figure 5 A typical annealing heat treatment applied to C-Mn and some low alloy steels.

3 Postweld Heat Treatment (PWHT)

Postweld heat treatment has to be applied to some welded steels to ensure that the properties of the weldment will be suitable for their intended applications.

The temperature at which PWHT is carried out is usually well below the temperature where phase changes can occur (see *Note*), but high enough to allow residual stresses to be relieved quickly and to soften (temper) any hard regions in the HAZ.

There are major benefits of reducing residual stress and ensuring that the HAZ hardness is not too high for steels for particular service applications.

- Improves the resistance of the joint to brittle fracture.
- Improves the resistance of the joint to stress corrosion cracking.
- Enables welded joints to be machined to accurate dimensional tolerances.

Because the main reason for (and benefit of) PWHT is to reduce residual stresses, PWHT is often called **stress-relief**.

Note: *There are circumstances when a welded joint may need to be normalised to restore HAZ toughness. However, these are relatively rare circumstances and it is necessary to ensure that welding consumables are carefully selected because normalising will significantly reduce weld metal strength.*

4 PWHT Thermal Cycle

The Application Standard/Code, will specify when PWHT is required to give the first two benefits above and also give guidance about the thermal cycle that must be used.

To ensure that a PWHT cycle is carried out in accordance with a particular Code, it is essential that a PWHT procedure is prepared and that the following parameters are specified:

Maximum heating rate.
Soak temperature range.
Minimum time at the soak temperature (soak time).
Maximum cooling rate.

4.1 Heating rate

This must be controlled to avoid large temperature differences within the fabricated item. Large differences in temperature (large thermal gradients) will produce large stresses and these may be high enough to cause distortion (or even cracking).

Application Standards usually require control of the maximum heating rate when the temperature of the item is above $\sim 300^{\circ}\text{C}$. This is because steels start to show significant loss of strength above this temperature and are more susceptible to distortion if there are large thermal gradients.

The temperature of the fabricated item must be monitored during the thermal cycle by means of thermocouples attached to the surface at locations representing the thickness range of the item.

By monitoring furnace and item temperatures the rate of heating can be controlled to ensure compliance with Code requirements **at all positions within the item**.

Maximum heating rates specified for C-Mn steel depend on thickness of the item but tend to be in the range ~ 60 to $\sim 200^{\circ}\text{C/h}$.

4.2 Soak temperature

The soak temperature specified by the Code depends on the type of steel and thus the temperature range required to reduce residual stresses to a low level.

C and C-Mn steels require a soak temperature of $\sim 600^{\circ}\text{C}$ whereas some low alloy steels (such as Cr-Mo steels used for elevated temperature service) require higher temperatures – typically in the range ~ 700 to $\sim 760^{\circ}\text{C}$.

Soak temperature is an essential variable for a WPQR. Thus, it is very important it is controlled within the specified limits otherwise it may be necessary to carry out a new WPQ test to validate the properties of the item and at worst it may not be fit-for-purpose.

4.3 Soak time

It is necessary to allow time for all the welded joints to experience the specified temperature throughout the full joint thickness.

The temperature is monitored by surface-contact thermocouples and it is the thickest joint of the fabrication that governs the minimum time for temperature equalisation.

Typical specified soak times are 1h per 25mm thickness.

4.4 Cooling rate

It is necessary to control the rate of cooling from the PWHT temperature for the same reason that heating rate needs to be controlled – to avoid distortion (or cracking) due to high stresses from thermal gradients.

Codes usually specify controlled cooling to $\sim 300^{\circ}\text{C}$. Below this temperature the item can be withdrawn from a furnace and allowed to cool in air because

steel is relatively strong and is unlikely to suffer plastic strain by any temperature gradients that may develop.

Figure 6 shows a typical PWHT thermal cycle.

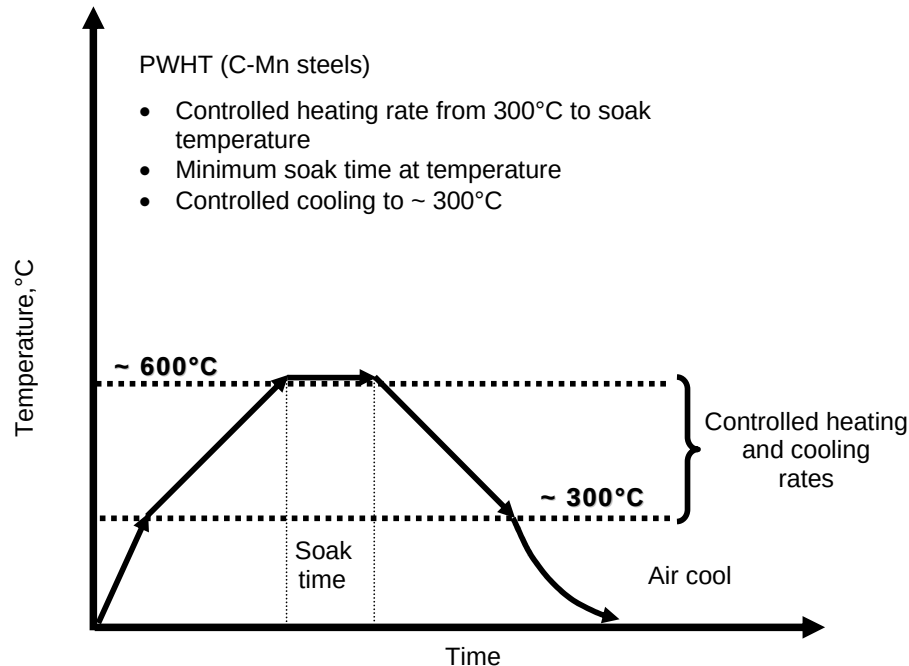


Figure 6 A typical PWHT applied to C-Mn steels.

5 Heat Treatment Furnaces

It is important that oil- and gas-fired furnaces used for PWHT do not allow flame contact with the fabrication as this may induce large thermal gradients.

It is also important to ensure that the fuel (particularly for oil-fired furnaces) does not contain high levels of potentially harmful impurities – such as sulphur.

6 Local PWHT

For a pipeline or pipe spool it is often necessary to apply PWHT to individual welds by local application of heat.

For this, a PWHT procedure must specify the previously described parameters for controlling the thermal cycle but it is also necessary to specify the following:

- Width of the heated band (that must be within the soak temperature range).
- Width of the temperature decay band (soak temperature to ~300°C).

Other considerations are:

- Position of the thermocouples within in the heated band width and the decay band.
- If the item needs to be supported in a particular way to allow movement/ avoid distortion.

The commonest method of heating for local PWHT is by means of insulated electrical elements (electrical mats) that are attached to the weld.

Gas-fired, radiant, heating elements can also be used.

Figure 7 shows typical control zones for localised PWHT of a pipe butt weld.

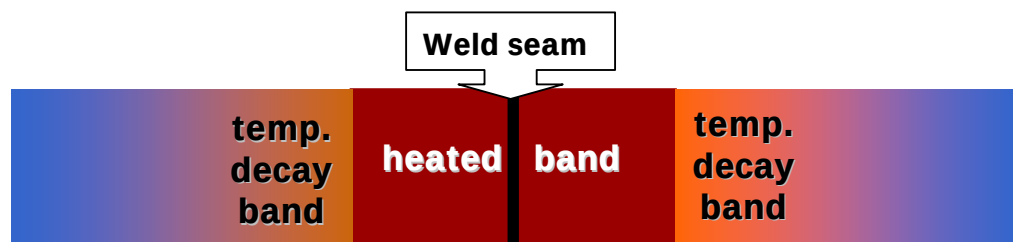


Figure 7 Local PWHT of a pipe girth seam.

1 General

Working in a safe manner, whether in the workshop or on site, is an important consideration in any welding operation. The responsibility for safety is on the individuals, not only for their own safety, but also for other people's safety. The Visual/Welding Inspector has an important function in ensuring that safe working legislation is in place and safe working practices are implemented. The Inspector may be required to carry out safety audits of welding equipment prior to welding, implement risk assessment/permit to work requirements or monitor the safe working operations for a particular task, during welding.

There are a number of documents that the inspector may refer to for guidance:

- Government legislation – The Health & Safety at Work Act.
- Health & Safety Executive – COSHH Regulations, Statutory instruments.
- Work or site instructions – permits to work, risk assessment documents etc.
- Local Authority requirements.

There are four aspects of arc welding safety that the Visual/Welding Inspector needs to consider:

- Electric shock.
- Heat and light.
- Fumes and gases.
- Noise.

2 Electric Shock

The hazard of electric shock is one of the most serious and immediate risks facing personnel involved in the welding operation.

Contact with metal parts, which are electrically hot, can cause injury or death because of the effect of the shock upon the body or because of a fall as a result of the reaction to electric shock.

The electric shock hazard associated with arc welding may be divided into two categories:

- Primary voltage shock – 230 or 460V
- Secondary voltage shock – 60 to 100V

Primary voltage shock is very hazardous because it is much greater than the secondary voltage of the welding equipment. Electric shock from the primary (input) voltage can occur by touching a lead inside the welding equipment with the power to the welder switched on while the body or hand touches the welding equipment case or other earthed metal. Residual circuit

devices (RCDs) connected to circuit breakers of sufficient capacity will help to protect the welder and other personnel from the danger of primary electric shock.

Secondary voltage shock occurs when touching a part of the electrode circuit – perhaps a damaged area on the electrode cable and another part of the body touches both sides of the welding circuit (electrode and work, or welding earth) at the same time.

Most welding equipment is unlikely to exceed OCVs of 100V. Electric shock, even at this level can be serious, so the welding circuit should be fitted with low voltage safety devices, to minimise the potential of secondary electric shock.

A correctly wired welding circuit should contain three leads:

- **Welding lead** from one terminal of the power source to the electrode holder or welding torch.
- **Welding return lead** to complete the circuit, from the work to the other terminal of the power source.
- **Earth lead** from the work to an earth point. The power source should also be earthed.

All three leads should be capable of carrying the highest welding current required.

To establish whether the capacity of any piece of current carrying equipment is adequate for the job, the Visual/ Welding Inspector can refer to the **duty cycle** of the equipment.

All current carrying welding equipment is rated in terms of:

Duty cycle

All current carrying conductors heat up when welding current is passed through them. Duty Cycle is essentially a measure of the capability of the welding equipment in terms of the ratio of welding time to total time, which can be expressed as:

$$\text{Duty cycle} = \frac{\text{Welding time}}{\text{Total time}} \times 100$$

By observing this ratio the current carrying conductors will not be heated above their rated temperature. Duty cycles are based on a total time of 10 minutes.

For example: A power source has a rated output of 350A at 60% duty cycle. This means that this particular power source will deliver 350A (its rated output) for six minutes out of every ten minutes without overheating.

Failure to carefully observe the duty cycle of equipment can over-stress the part, and in the case of welding equipment cause overheating leading to instability and the potential for electric shock.

3 Heat and Light

3.1 Heat

In arc welding, electrical energy is converted into heat and light energies, both of which can have serious health consequences.

The welding arc creates sparks, which have the potential to cause flammable materials near the welding area to ignite and cause fires. The welding area should be clear of all combustible materials and is good practice for the Inspector to know where the nearest fire extinguishers are and the correct type of fire extinguisher to use if a fire does break out.

Welding sparks can cause serious burns, so protective clothing, such as welding gloves, flame retardant coveralls and leathers must be worn around any welding operation to protect against heat and sparks.

3.2 Light

Light radiation is emitted by the welding arc in three principal ranges:

Type	Wavelength, nanometres
Infra red (heat)	>700
Visible light	400-700
Ultra violet radiation	<400

3.2.1 Ultra violet radiation (UV)

All arc processes generate UV and excess exposure causes skin inflammation, and possibly even skin cancer or permanent eye damage. However, the main risk amongst welders and Inspectors is inflammation of the cornea and conjunctiva, commonly known as arc eye or flash.

Arc eye is caused by UV radiation which damages the outmost protective layer of cells in the cornea. Gradually the damaged cells die and fall off the cornea exposing highly sensitive nerves in the underlying cornea to the comparatively rough inner part of the eyelid. This causes intense pain, usually described as sand in the eye. The pain becomes even more acute if the eye is then exposed to bright light.

Arc eye develops some hours after exposure, which may not even have been noticed. The sand in the eye symptom and pain usually lasts for 12-24 hours, but can be longer in more severe cases. Fortunately, arc eye is almost always a temporary condition. In the unlikely event of prolonged and frequently repeated exposures, permanent damage can occur.

Treatment of arc eye is simple: rest in a dark room. A qualified person or hospital casualty department can administer various soothing anaesthetic eye drops which can provide almost instantaneous relief. Prevention is better than cure and wearing safety glasses with side shields will considerably reduce the risk of this condition.

3.2.2 Ultra violet effects upon the skin

The UV from arc processes does not produce the browning effect of sunburn; but does result in reddening and irritation caused by changes in the minute surface blood vessels. In extreme cases, the skin may be severely burned and blisters may form. The reddened skin may die and flake off in a day or so. Where there has been intense prolonged or frequent exposure, skin cancers can develop.

3.2.3 Visible light

Intense visible light particularly approaching UV or blue light wavelengths passes through the cornea and lens and can dazzle and, in extreme cases, damage the network of optically sensitive nerves on the retina. Wavelengths of visible light approaching infra red have slightly different effects but can produce similar symptoms. Effects depend on the duration and intensity of exposure and to some extent, upon the individual's natural reflex action to close the eye and exclude the incident light. Normally this dazzling does not produce a long-term effect.

3.2.4 Infra red radiation

Infra red radiation is of longer wavelength than the visible light frequencies, and is perceptible as heat. The main hazard to the eyes is that prolonged exposure (over a matter of years) causes a gradual but irreversible opacity of the lens. Fortunately, the infra red radiation emitted by normal welding arcs causes damage only within a comparatively short distance from the arc. There is an immediate burning sensation in the skin surrounding the eyes should they be exposed to arc heat. The natural human reaction is to move or cover up to prevent the skin heating, which also reduces eye exposure.

BS EN 169 specifies a range of permanent filter shades of gradually increasing optical density which limit exposure to radiation emitted by different processes at different currents. It must be stressed that shade numbers indicated in the standard and the corresponding current ranges are for guidance only.

4 Fumes and Gases

4.1 Fumes

Because of the variables involved in fume generation from arc welding and allied processes (such as the welding process and electrode, the base metal, coatings on the base metal and other possible contaminants in the air), the dangers of welding fume can be considered in a general way. Although health considerations vary according to the type of fume composition and individual reactions, the following holds true for most welding fume.

The fume plume contains solid particles from the consumables, base metal and base metal coating. Depending on the length of exposure to these fumes, most acute effects are temporary and include symptoms of burning eyes and skin, dizziness, nausea and fever.

For example, zinc fumes can cause metal fume fever, a temporary illness similar to flu. Chronic, long-term exposure to welding fumes can lead to siderosis (iron deposits in the lungs) and may affect pulmonary function.

Cadmium, however, is a different story. This toxic metal can be found on steel as a coating or in silver solder. Cadmium fumes can be fatal even under brief exposure, with symptoms much like those of metal fume fever. These two should not be confused. Twenty minutes of welding in the presence of cadmium can be enough to cause fatalities, with symptoms appearing within an hour and death five days later.

4.2 Gases

The gases that result from arc welding also present a potential hazard. Most of the shielding gases (argon, helium and carbon dioxide) are non-toxic, when released, however, these gases displace oxygen in the breathing air, causing dizziness, unconsciousness and death the longer the brain is denied oxygen.

Some degreasing compounds such as trichlorethylene and perchlorethylene can decompose from the heat and UV radiation to produce toxic gases. Ozone and nitrogen oxides are produced when UV radiation hits the air and can cause headaches, chest pains, irritation of the eyes and itchiness in the nose and throat.

To reduce the risk of hazardous fumes and gases, keep the head out of the fume plume. As obvious as this sounds, it is a common cause of fume and gas over-exposure because the concentration of fumes and gases is greatest in the plume.

In addition, use mechanical ventilation or local exhaust at the arc to direct the fume plume away from the face. If this is not sufficient, use fixed or moveable exhaust hoods to draw the fume from the general area. Finally, it may be necessary to wear an approved respiratory device if sufficient ventilation cannot be provided.

As a rule of thumb, if the air is visibly clear and the welder is comfortable, the ventilation is probably adequate.

To identify hazardous substances, first read the material safety data sheet for the consumable to see what fumes can be reasonably expected from use of the product.

Refer to the Occupational Exposure Limit (OEL) as defined in the COSHH regulations which gives maximum concentrations to which a healthy adult can be exposed to any one substance.

Second, know the base metal and determine if a paint or coating would cause toxic fumes or gases.

Particular attention should also be made to the dangers of asphyxiation when welding in confined spaces. Risk assessment, permits to work and gas testing are some of the necessary actions required to ensure the safety of all personnel.

Noise

Exposure to loud noise can permanently damage hearing, cause stress and increase blood pressure. Working in a noisy environment for long periods can contribute to tiredness, nervousness and irritability. If the noise exposure is greater than 85 decibels averaged over an 8 hour period then hearing protection must be worn, and annual hearing tests carried out.

Normal welding operations are not associated with noise level problems with two exceptions: Plasma arc welding and air carbon arc cutting. If either of these two operations is to be performed then hearing protectors must be worn. The noise associated with welding is usually due to ancillary operations such as chipping, grinding and hammering. Hearing protection must be worn when carrying out, or when working in the vicinity of, these operations.

5 Summary

The best way to manage the risks associated with welding is by implementing risk management programmes. Risk management requires the identification of hazards, assessment of the risks and implementation of suitable controls to reduce the risk to an acceptable level.

It is essential to evaluate and review a risk management programme. Evaluation involves ensuring that control measures have eliminated or reduced the risks and review the aims to check that the process is working effectively to identify hazards and manage risks.

It is quite likely that the Visual/Welding Inspector would be involved in managing the risks associated with welding as part of their duties.

1 Introduction

BS 7570 - Code of practice for validation of arc welding equipment – is a standard that gives guidance to:

- Manufacturers about the accuracy required from output meters fitted to welding equipment to show welding current, voltage, etc.
- End users who need to ensure that output meters provide accurate readings.

The Standard refers to two grades of equipment – standard and precision grade.

Standard grade equipment is suitable for manual and semi-automatic welding processes.

Precision grade equipment is intended for mechanised or automatic welding because there is usually a need for greater precision for all welding variables as well as the prospect of the equipment being used for higher duty cycle welding.

2 Terminology

BS 7570 defines the terms it uses, such as:

Calibration	Operations for the purpose of determining the magnitude of errors of a measuring instrument etc.
Validation	Operations for the purpose of demonstrating that an item of welding equipment, or a welding system, conforms to the operating specification for that equipment or system.
Accuracy	Closeness of an observed quantity to the defined, or true, value.

Thus, when considering welding equipment, those that have output meters for welding parameters (current, voltage, travel speed, etc.) can be calibrated by checking the meter reading with a more accurate measuring device – and adjusting the readings appropriately.

Equipment that does not have output meters (some power sources for MMA, MIG/MAG) cannot be calibrated but they can be validated, that is to make checks to see the controls are functioning properly.

3 Calibration Frequency

BS 7570 recommends re-calibration/validation at:

- Yearly intervals (following an initial consistency test at three monthly intervals) for standard grade equipment.
- Six monthly intervals for precision grade equipment.

However, the Standard also recommends that re-calibration/validation may be necessary more frequently. Factors that need to be considered are:

- Equipment manufacturer's recommendations.
- User's requirements.
- If the equipment has been repaired re-calibration should always be carried out.
- There is a reason to believe the performance of the equipment has deteriorated.

4 Instruments for Calibration

Instruments used for calibration should:

- Be calibrated by a recognised calibrator – using standards that are traceable to a national standard.
- Be at least twice, and preferably five times, more accurate than the accuracy required for the grade of equipment.
- For precision grade equipment it will be necessary to use instruments with much greater precision for checking output meters.

5 Calibration Methods

The Standard gives details about the characteristics of power source types, how many readings should be taken for each parameter and guidance on precautions that may be necessary.

For the main welding parameters, recommendations from the Standard are as follows.

Current

Details are given about the instrumentation requirements and how to measure pulsed current but there are requirements given, specified, or recommendations made, about where in the circuit current measurements should be made.

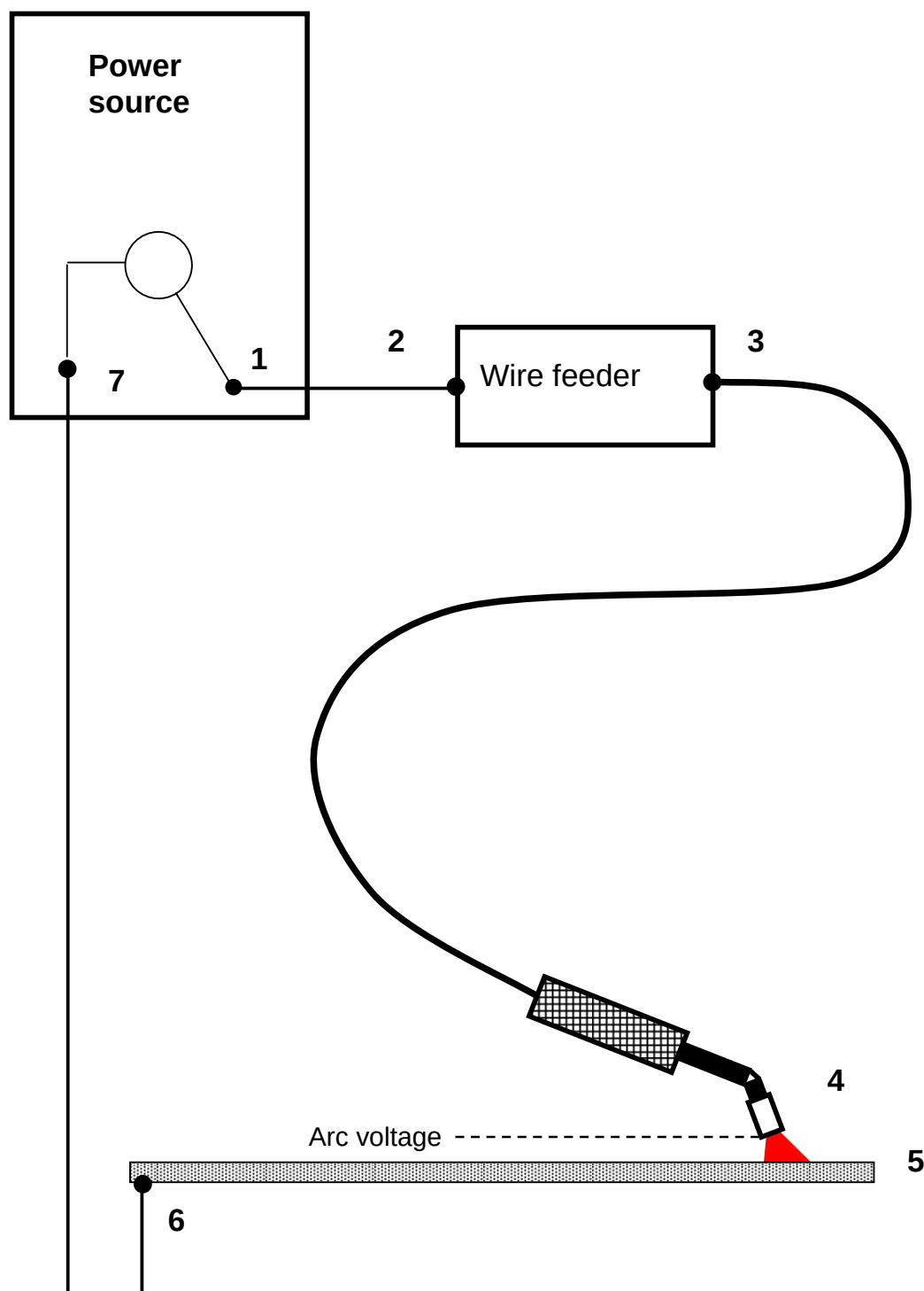
The implication is that current can be measured at any position in the circuit – the value should be the same.

Voltage

The standard emphasises that for processes where voltage is pre-set (on constant voltage the power sources) the connection points used for the voltage meter incorporated into the power source may differ from the **arc** voltage, which is the important parameter.

To obtain an accurate measure of arc voltage, the voltage meter should be positioned as near as practical to the arc.

This is illustrated by the figure which shows the power source voltage meter connected across points 1 and 7.



A welding circuit (for MIG/MAG)

However, because there will be some voltage drops in sections 1-2, 3-4 and 6-7 due to connection points introducing extra resistance into the circuit, the voltage meter reading on the power source will tend to give a higher reading than the true arc voltage.

Even if the power source voltage meter is connected across points 3 and 7 (which it may be) the meter reading would not take account of any significant voltage drops in the return cable – Section 6-7.

The magnitude of any voltage drops in the welding circuit will depend on cable diameter, length and temperature and the Standard emphasises the following:

- It is desirable to measure the true arc voltage between points 4-5 but for some welding processes it is not practical to measure arc voltage so close to the arc.
- For MMA, it is possible to take a voltage reading relatively close to the arc by connecting one terminal of the voltmeter through the cable sheath as close as ~2m from the arc and connect the other terminal to the workpiece (or to earth).
- For MIG/MAG the nearest practical connection points have to be 3-5 but a change from an air to a water-cooled torch or vice-versa may have a significant affect on the measured voltage.
- Voltage drops between points 5-6 will be insignificant if there is a good connection of the return cable at point 6.

The Standard gives guidance about minimising any drop in line voltage by ensuring that the:

- Current return cable is as short as practical and is heavy, low resistance, cable
- Current/return connector is suitably rated and firmly attached so does not overheat due to high resistance

The Standard gives data for line voltage drops (DC voltage) according to current, cable cross-section and length (for both copper and aluminium cables).

Wire feed speed

For constant voltage (self-adjusting arc) processes such as MIG/MAG the standard recognises that calibration of the wire feeder is generally not needed because it is linked to current.

If calibration is required, it is recommended that the time is measured (in seconds) for ~1m of wire to be delivered (using a stopwatch or an electronic timer).

The length of wire should then be measured (with a steel rule) to an accuracy of 1mm and the feed speed calculated.

Travel speed

Welding manipulators, such as rotators and robotic manipulators, as well as the more conventional linear travel carriages, influence heat input and other properties of a weld and should be checked at intervals.

Most of the standard devices can be checked using a stopwatch and measuring rule, but more sophisticated equipment, such as a tachogenerator, may be appropriate.

1 General

Preheat is the application of heat to a joint immediately prior to welding and is usually applied by either a gas torch or induction system, although other methods can be used.

Preheat is used when welding steels for a number of reasons and it helps to understand why it is often specified in the first place, one of the main reasons is to assist in removing hydrogen from the weld.

Preheat temperatures for steel structures and pipework are calculated by taking into account the carbon equivalent (CEV) and thickness of the material and the arc energy or heat input (kJ/mm) of the welding process.

Standards such as BS EN 1011: 'Recommendations for welding of metallic materials for guidance on selection of preheat temperature ranges based on CEV, material thickness, arc energy/heat input, and the lowest level of diffusible hydrogen required.

The Visual/Welding Inspector would normally find the preheat temperature for a particular application from the relevant WPS.

In general, thicker materials require higher preheat temperatures, but for a given CEV and arc energy/heat input, they are likely to remain similar for wall thickness up to approximately 20mm.

2 Definitions

Preheat temperature

- The temperature of the work piece in the weld zone immediately before any welding operation (including tack welding!).
- Normally expressed as a minimum, but can also be specified as a range.

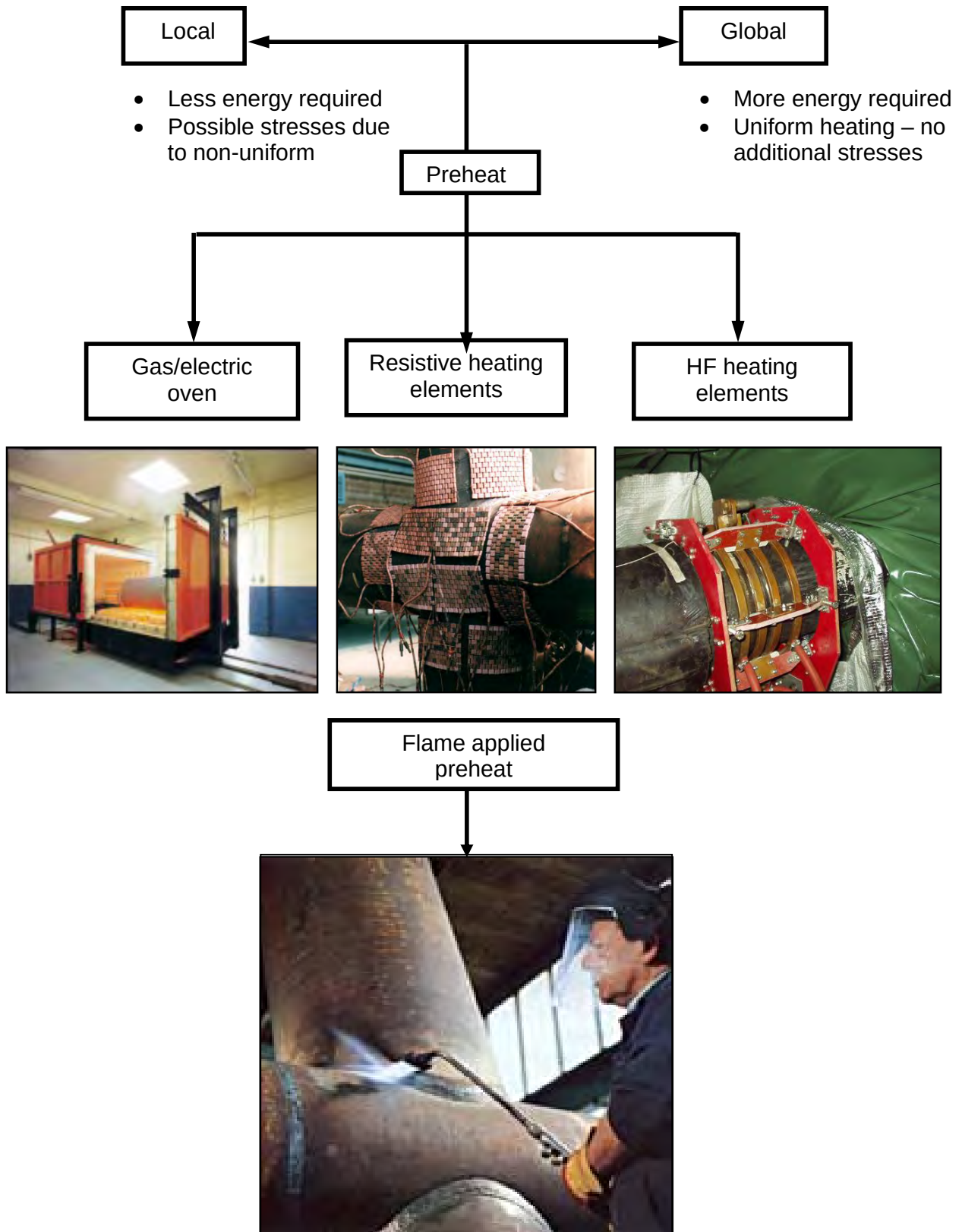
Interpass temperature

- The temperature of the weld during welding and between passes in a multi-run weld and adjacent parent metal immediately prior to the application of the next run.
- Normally expressed as a maximum, but should not drop below the minimum preheat temperature.

Preheat maintenance temperature

- Minimum temperature in the weld zone which should be maintained if welding is interrupted.
- Should be monitored during interruption.

3 Application of Preheat



Gas/electric ovens

Generally used for PWHT but can be used for large sections of material to give a controlled and uniform preheat.

Resistive heating elements

Heating using electric current flowing through resistance coils.

High frequency heating elements

The heating effect is produced electrostatically, providing uniform heating through a mass of material. Heat is generated by the agitation of the molecules in the material when subjected to a high frequency field.

Flame applied preheat

Probably the most common method of applying preheat using either torches or burners. Oxygen is an essential part of the preheating flame, as it supports combustion, but the fuel gases can be acetylene, propane or methane (natural gas).

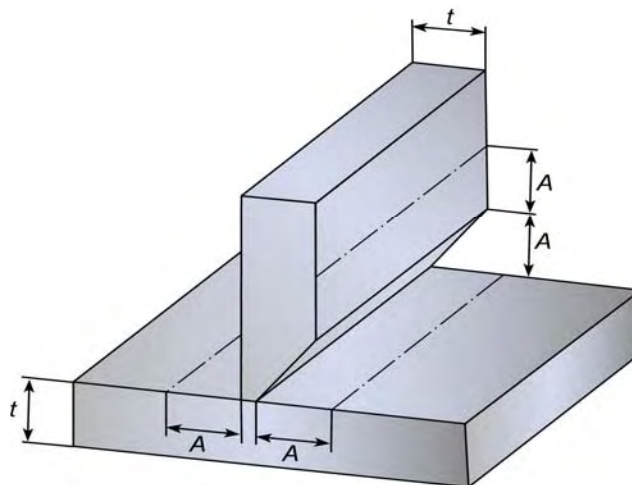
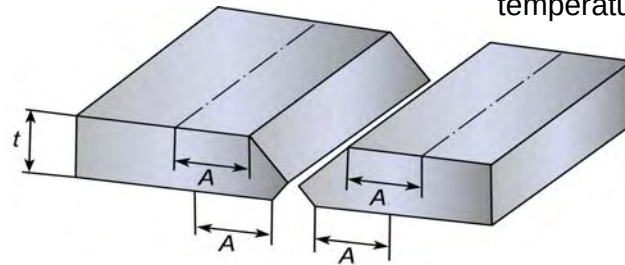
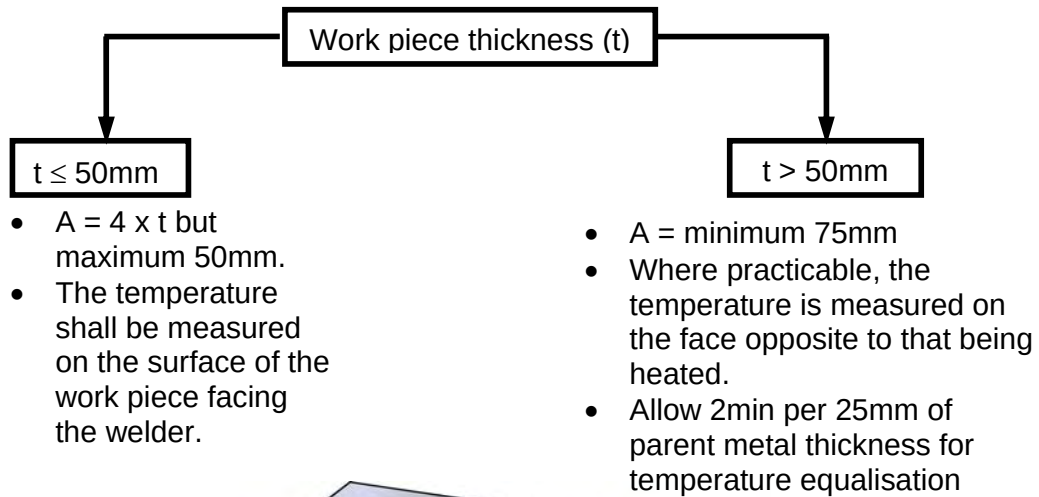
With flame applied preheating sufficient time must be allowed for the temperature to equalise throughout the thickness of the components to be welded, otherwise only the surface temperature will be measured. The time lapse will vary depending on the specification requirements.

4 Control of Preheat and Interpass Temperature

When?

Immediately before passage of the arc

Where?

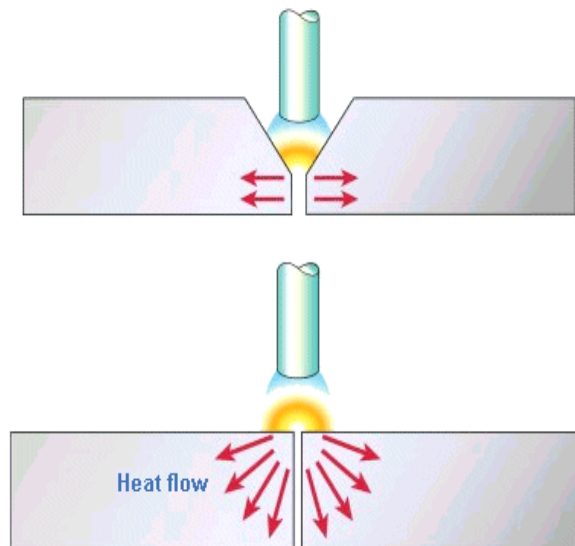
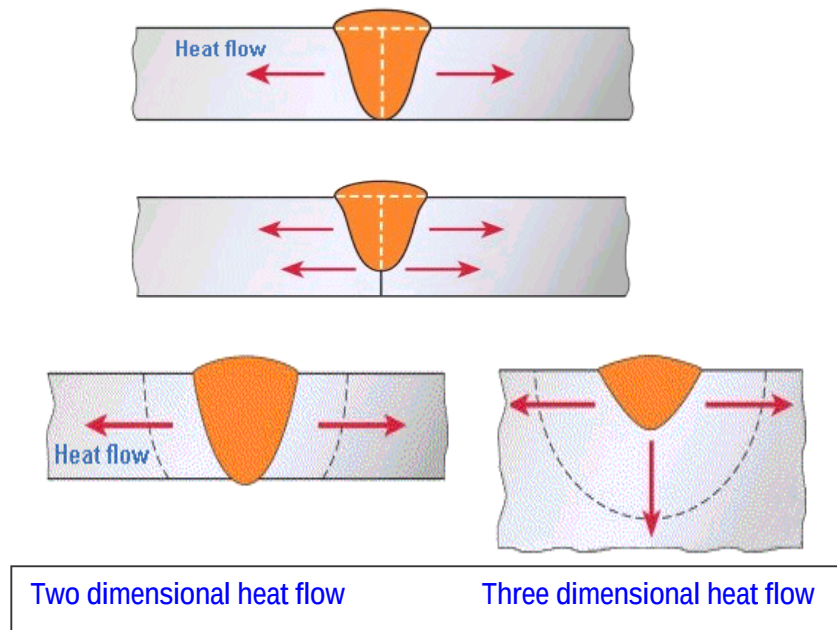


Interpass temperature is measured on the weld metal or the immediately adjacent parent metal.

Why?

Applying preheat has the following advantages:

- It slows down the cooling rate of the weld and HAZ; reducing the risk of hardened microstructures forming; allowing absorbed hydrogen more opportunity of diffusing out, thus reducing the potential for cracking.
- Removes moisture from the region of the weld preparation.
- Improves overall fusion characteristics during welding.
- Ensures more uniform expansion and contraction; lowering stresses between weld and parent material.



Temperature indicating/measuring equipment.

4.1 Temperature sensitive materials

- Made of a special wax that melts at a specific temperature (Tempilstik™) or irreversible colour change (Thermochrome™).
- Cheap, easy to use.
- Doesn't measure the actual temperature.



Examples of temperature indicating crayons and paste.

4.2 Contact thermometer

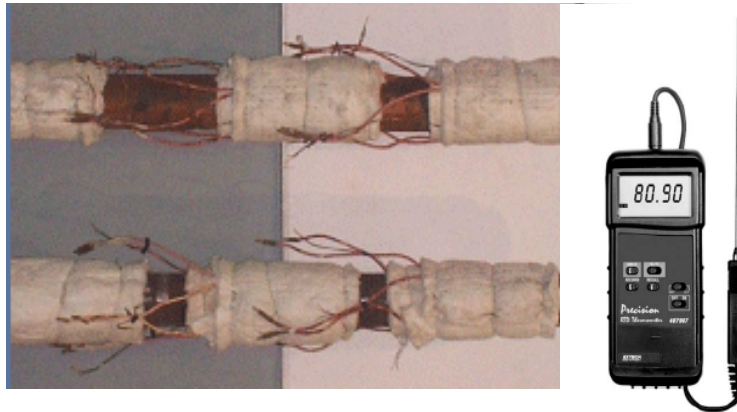
- Can use either a bimetallic strip or a thermistor (ie a temperature-sensitive resistor whose resistance varies inversely with temperature).
- Accurate, gives the actual temperature.
- Need calibration.
- Used for moderate temperatures (up to 350°C).



Examples of a contact thermometer.

4.3 Thermocouple

- Based on measuring the thermoelectric potential difference between a hot junction (placed on the weld) and a cold junction (reference junction).
- Measures wide range of temperatures.
- Accurate, gives the actual temperature.
- Can be used also for continuous monitoring.
- Need calibration.



Examples of thermocouples.

4.4 Optical or electrical devices for contactless measurement

- Can be infra red or optical pyrometers.
- Measure the radiant energy emitted by the hot body.
- Can be used for remote measurements.
- Very complex and expensive equipment.
- Normally used for measuring high temperatures.



Example of contactless temperature measuring equipment.

5 Summary

The Visual/Welding Inspector should refer to the WPS for both preheat and interpass temperature requirements. If in any doubt as to where the temperature measurements should be taken, the Senior Welding Inspector or Welding Engineer should be consulted for guidance.

Both preheat and interpass temperatures are applied to slow down the cooling rate during welding, avoiding the formation of brittle microstructures (ie martensite) and thus preventing cold cracking.

Preheat temperatures can be calculated using different methods as described in various standards (eg BS EN 1011-2, AWS D1.1, etc) and are validated during the qualification of the welding procedure.

According to BS EN ISO 15614 and ASME IX both preheat and interpass temperatures are considered to be essential variables, hence any change outside the range of qualification requires a new procedure qualification.

The practical visual inspection part of the **AWS-CSWIP** examination consists of the following categories:

AWS-CSWIP 3.1 Welding Inspector

Exam: Time allowed

Practical butt welded pipe (specification supplied) 1 hour 45 minutes.

*Practical assessment of 1 macro (**code provided**) 20 minutes.

To successfully attempt the practical inspection elements of these examinations the inspector will require a number of important tools:

- 1 Good eyesight.
- 2 Specialist gauges.
- 3 Hand tools, ie magnifying glass, torch, mirror, graduated scale, etc.
- 4 Pencil/pen, report forms, acceptance criteria and a watch.

Good eyesight

To effectively carry out your scope of work as a CSWIP qualified Welding Inspector it is important that you have a current eyesight certificate for close vision and a colour blindness test is also required. This must be provided before your CSWIP Welding Inspection examination, as per the CSWIP-WI-6-92 document.

All candidates for CSWIP examinations must be tested by a **qualified optician**.

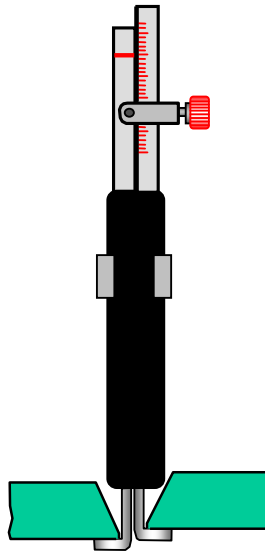
Holders of CSWIP Welding Inspection certificates should thus make every effort to have their vision professionally tested twice yearly.

It is important to maintain this level of eyesight. **Note:** Your close vision ability may decay over time.

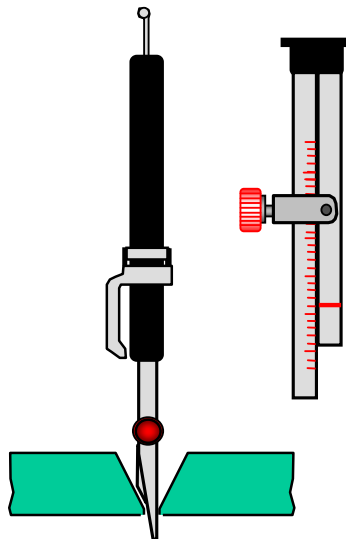
Specialist gauges

A number of specialist gauges are available to measure the various elements that need to be measured in a welded fabrication including:

- **Hi-lo gauges** for measuring mismatch and root gap.
- **Fillet weld profile gauges** for measuring fillet weld face profile and sizes.
- **Angle gauges** for measuring weld preparation angles.
- **Multi-functional weld gauges** for measuring many different weld measurements.



Hi-lo gauge used to measure linear misalignment.



Hi-lo gauge can also be used to measure the root gap.



Adjustable fillet gauge

Measures fillet welds from 3-25mm ($\frac{1}{8}$ -1 inch) with $\pm 0.8\text{mm}$ ($\frac{1}{32}$ inch) accuracy. It uses an offset arm, which slides at a 45° angle to make fillet weld length measurements. This gauge also measures weld throat thickness to 1.5mm ($\frac{1}{16}$ inch).



Fillet weld gauge

Measures weld sizes from 3mm ($\frac{1}{8}$ inch) up to 25mm (1 inch).



Multi-purpose welding gauge

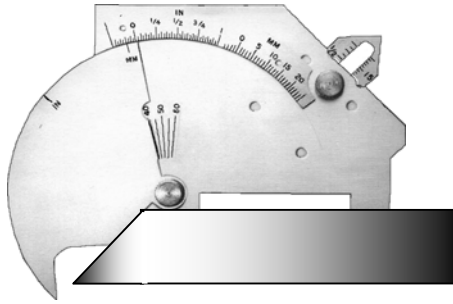
This rugged gauge, fabricated in stainless steel, will measure the important dimensions of weld preparations and of completed butt and fillet welds. It is intended for general fabrication work and rapidly measures angle of preparation, excess weld metal, fillet weld leg length and throat size, and misalignment in both metric and imperial.



Digital multi-purpose welding gauge

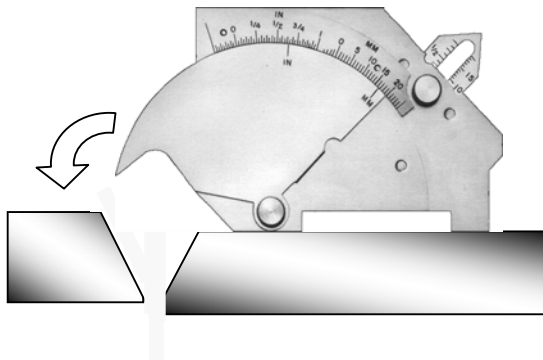
This digital gauge will measure the important dimensions of weld preparations and completed butt and fillet welds. It is intended for general fabrication work and rapidly measures angle of preparation, excess weld metal, fillet weld leg length and throat size in both metric and imperial.

TWI Cambridge multi-purpose welding gauge



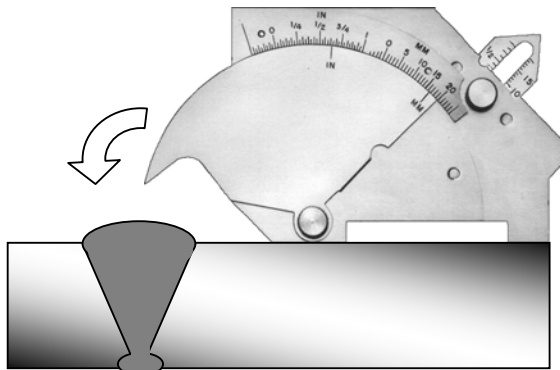
Angle of preparation

This scale reads 0 to 60° in 5° steps. The angle is read against the chamfered edge of the plate or pipe.



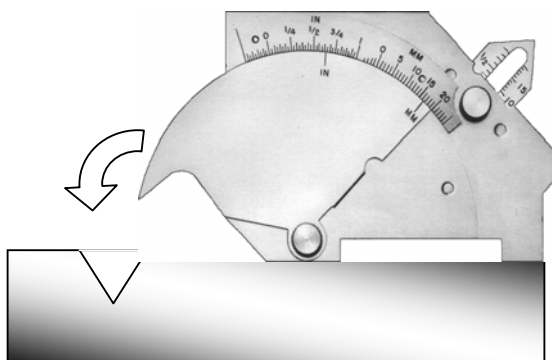
Linear misalignment

The gauge can be used to measure misalignment of members by placing the edge of the gauge on the lower member and rotating the segment until the pointed finger contacts the higher member.



Excess weld metal/root penetration

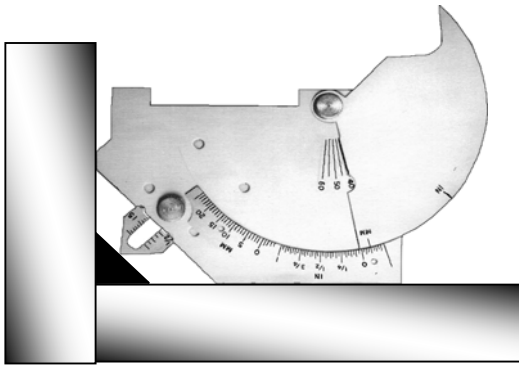
The scale is used to measure excess weld metal height or root penetration bead height of single-sided butt welds, by placing the edge of the gauge on the plate and rotating the segment until the pointed finger contacts the excess weld metal or root bead at its highest point.



Pitting/mechanical damage, etc

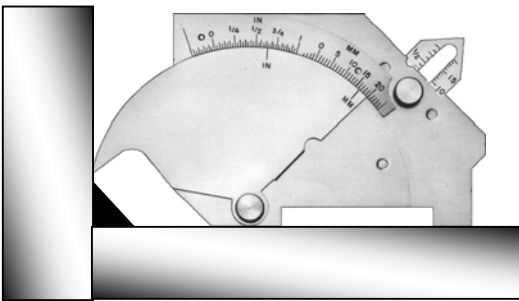
The gauge can be used to measure defects by placing the edge of the gauge on the plate and rotating the segment until the pointed finger contacts the lowest depth.

The reading is taken on the scale to the left of the zero mark in mm or inches.



Fillet weld actual throat thickness

The small sliding pointer reads up to 20mm ($\frac{3}{4}$ inch). When measuring the throat it is supposed that the fillet weld has a **nominal design throat** thickness, as an **effective design throat** thickness cannot be measured in this manner.



Fillet weld leg length

The gauge may be used to measure fillet weld leg lengths up to 25mm (1 inch), as shown on the left.

Excess weld metal can be easily calculated by measuring the leg length, and multiplying it by 0.7 This value is then subtracted from the measured throat thickness = excess weld metal.

Example: For a measured leg length of 10mm and a throat thickness of 8mm $10 \times 0.7 = 7$ (throat thickness 8) - 7 = 1mm of excess weld metal.

1 Macro-examination

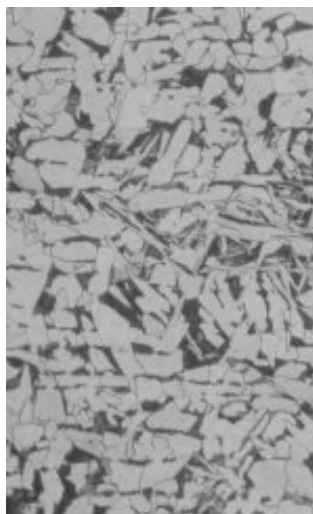
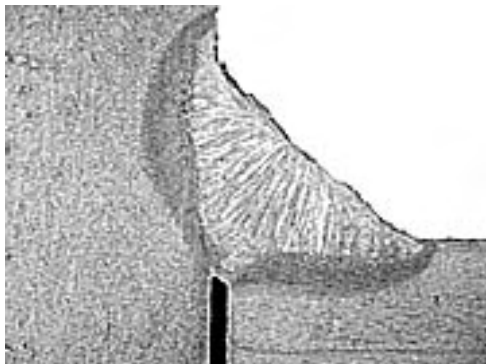
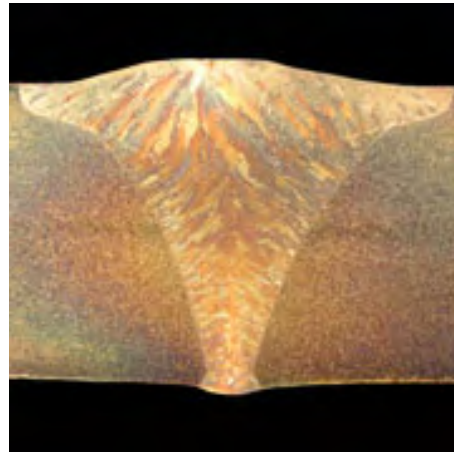
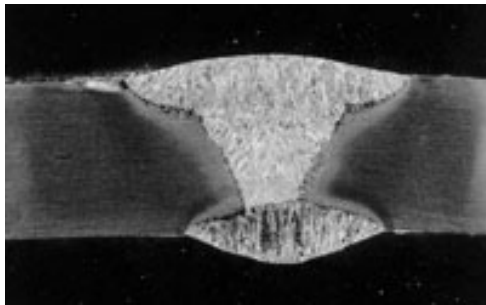
Macro-etching is the procedure in which a specimen is etched and evaluated macrostructurally at low magnifications. It is frequently used for evaluating carbon and low alloy steel products such as billets, bars, blooms and forgings as well as welds. There are several procedures for rating a steel specimen by a graded series of photographs showing the incidence of certain conditions and is applicable to carbon and low alloy steels. A number of different etching reagents may be used depending upon the type of examination. Steels react differently to etching reagents because of variations in chemical composition, method of manufacture, heat treatment and many other variables.

Macro-examinations are also performed on a polished and etched cross-section of a welded material. During the examination, a number of features can be determined including weld run sequence, important for weld procedure qualifications tests. As well as this, any defects on the sample will be assessed for compliance with relevant specifications. Slag, porosity, lack of weld penetration, lack of sidewall fusion and poor weld profile are among the features observed in such examinations. It is normal to look for such defects either by standard visual examination or at magnifications of up to 5X. It is also routine to photograph the section to provide a permanent record, this is known as a photomacrograph.

2 Micro-examination

This is performed on samples either cut to size or mounted in a resin mould. The samples are polished to a fine finish, normally one-micron diamond paste and usually etched in an appropriate chemical solution prior to examination on a metallurgical microscope. Micro-examination is performed for a number of purposes, the most obvious of which is to assess the structure of the material. It is also common to examine for metallurgical anomalies such as third phase precipitates, excessive grain growth, etc. Many routine tests such as phase counting or grain size determinations are performed in conjunction with micro-examinations.

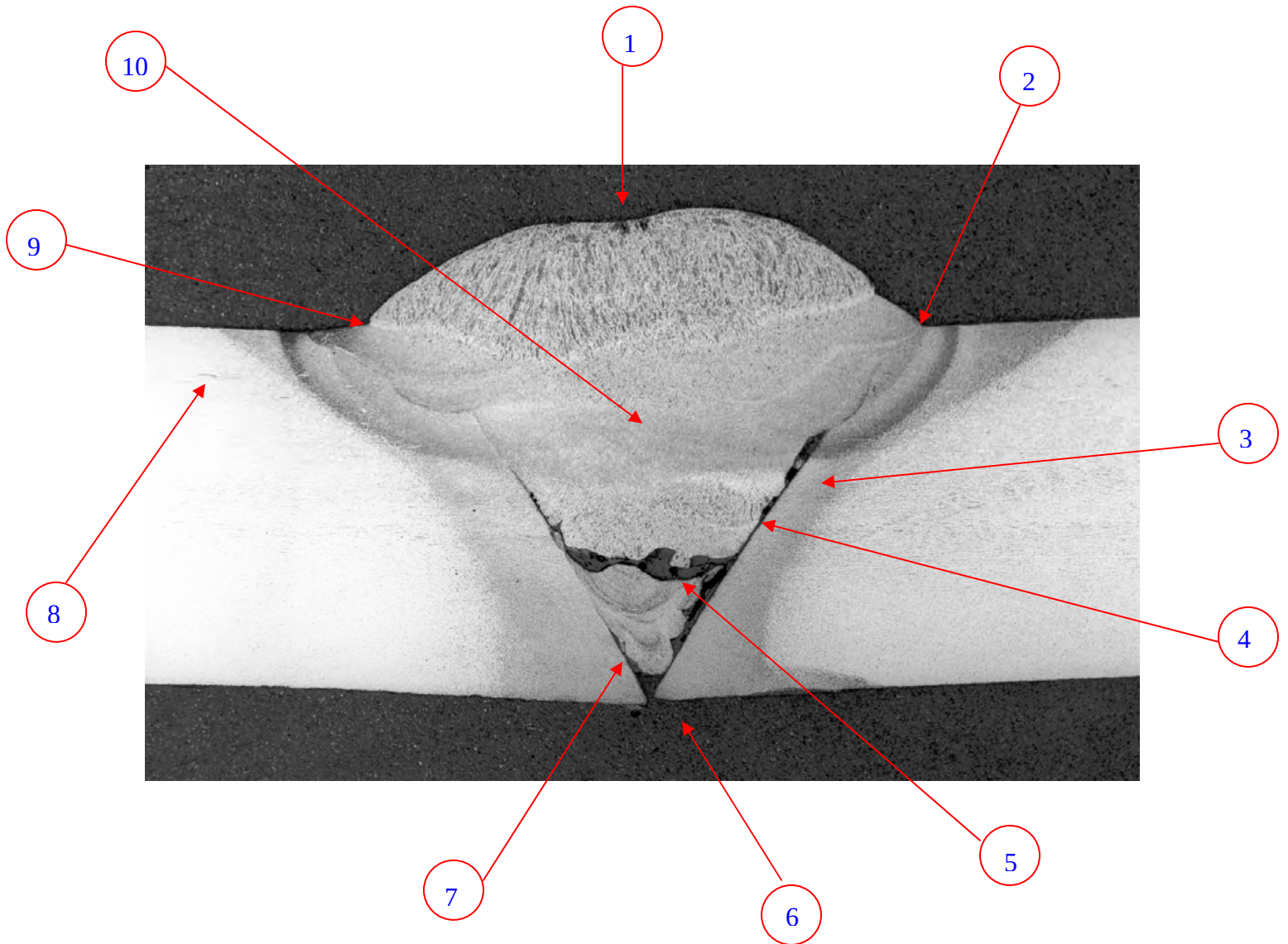
Metallographic weld evaluations can take many forms. In its most simple form, a weld deposit can be visually examined for large-scale defects such as porosity or lack of fusion defects. On a microscale, the examination can take the form of phase balance assessments from weld cap to weld root or a check for non-metallic or third phase precipitates. Examination of weld growth patterns is also used to determine reasons for poor mechanical test results. For example, an extensive central columnar grain pattern can cause a plane of weakness giving poor Charpy results.



Photomacrographs.

Training Macro 1

Welding process used MMA (SMAW)



These questions to be used with training macro 1

1. What is the indication at position 1 and would you accept or reject the indication to the given acceptance levels?
 - a. Slag inclusions
 - b. Porosity
 - c. Excessive grain size
 - d. Tungsten inclusions
 - e. Accept
 - f. Reject
2. The area identified at position 2 is referred to as the?
 - a. Fusion zone
 - b. Fusion boundary
 - c. Toe of the weld
 - d. Under cut
3. The area identified at position 3 is referred to as the?
 - a. Fusion boundary
 - b. Acid marks
 - c. Polished area
 - d. Heat affected zone
4. What is the indication at position 4 and would you accept or reject the indication to the given acceptance levels?
 - a. lack of inter run fusion
 - b. fusion boundary
 - c. lack of side wall fusion
 - d. linear crack
 - e. Accept
 - f. Reject
5. What is the indication at position 5 and would you accept or reject the indication to the given acceptance levels?
 - a. Gas cavity
 - b. Lack of side wall fusion
 - c. Slag trapped at the toes of the weld
 - d. Lack of inter run fusion and slag
 - e. Accept
 - f. Reject

6. What is the indication at position 6 and would you accept or reject the indication to the given acceptance levels?
- a. Slag inclusion
 - b. Lack of root fusion
 - c. Lack of root penetration
 - d. Burn through
 - e. Accept
 - f. Reject
7. What is the indication at position 7 and would you accept or reject the indication to the given acceptance levels?
- a. Lack of inter run fusion
 - b. Lack of side wall fusion
 - c. Crack
 - d. Porosity in the root
 - e. Accept
 - f. Reject
8. What is the indication at position 8 and would you accept or reject the indication to the given acceptance levels?
- a. lamellar tearing
 - b. Hydrogen cracks
 - c. Laminations
 - d. Stress cracks
 - e. Accept
 - f. Reject
9. What is the indication at position 9 and would you accept or reject the indication to the given acceptance levels?
- a. Overlap
 - b. Toe of the weld with good transition
 - c. Toe of the weld with poor transition
 - d. Undercut at the toe of the weld
 - e. Accept
 - f. Reject
10. Which term best describes this welded joint?
- a. Square edge butt joint
 - b. Double v butt joint
 - c. Single v butt joint
 - d. T butt fillet weld

Training Macro Answer Sheet

Macro 1						
1	1a	1b	1c	1d	1e	1f
2	2a	2b	2c	2d	2e	2f
3	3a	3b	3c	3d	3e	3f
4	4a	4b	4c	4d	4e	4f
5	5a	5b	5c	5d	5e	5d
6	6a	6b	6c	6d	6e	6f
7	7a	7b	7c	7d	7e	7f
8	8a	8b	8c	8d	8e	8f
9	9a	9b	9c	9d	9e	9f
10	10a	10b	10c	10d	10e	10f

Macro 2						
1	1a	1b	1c	1d	1e	1f
2	2a	2b	2c	2d	2e	2f
3	3a	3b	3c	3d	3e	3f
4	4a	4b	4c	4d	4e	4f
5	5a	5b	5c	5d	5e	5f
6	6a	6b	6c	6d	6e	6f
7	7a	7b	7c	7d	7e	7f
8	8a	8b	8c	8d	8e	8f
9	9a	9b	9c	9d	9e	9f
10	10a	10b	10c	10d	10e	10f

Macro 3						
1	1a	1b	1c	1d	1e	1f
2	2a	2b	2c	2d	2e	2f
3	3a	3b	3c	3d	3e	3f
4	4a	4b	4c	4d	4e	4f
5	5a	5b	5c	5d	5e	5f
6	6a	6b	6c	6d	6e	6f
7	7a	7b	7c	7d	7e	7f
8	8a	8b	8c	8d	8e	8f
9	9a	9b	9c	9d	9e	9f
10	10a	10b	10c	10d	10e	10f

Macro 4						
1	1a	1b	1c	1d	1e	1f
2	2a	2b	2c	2d	2e	2f
3	3a	3b	3c	3d	3e	3f
4	4a	4b	4c	4d	4e	4f
5	5a	5b	5c	5d	5e	5f
6	6a	6b	6c	6d	6e	6f
7	7a	7b	7c	7d	7e	7f
8	8a	8b	8c	8d	8e	8f
9	9a	9b	9c	9d	9e	9f
10	10a	10b	10c	10d	10e	10f

Macro 5						
1	1a	1b	1c	1d	1e	1f
2	2a	2b	2c	2d	2e	2f
3	3a	3b	3c	3d	3e	3f
4	4a	4b	4c	4d	4e	4f
5	5a	5b	5c	5d	5e	5f
6	6a	6b	6c	6d	6e	6f
7	7a	7b	7c	7d	7e	7f
8	8a	8b	8c	8d	8e	8f
9	9a	9b	9c	9d	9e	9f
10	10a	10b	10c	10d	10e	10f

CSWIP VISUAL INSPECTION PIPE REPORT

Name [Block capitals] _____ Signature_____ Pipe Ident#_____

Code/Specification used_____ Welding Process_____ Joint type_____

Welding position_____ Outside Ø & Thickness_____ Date _____

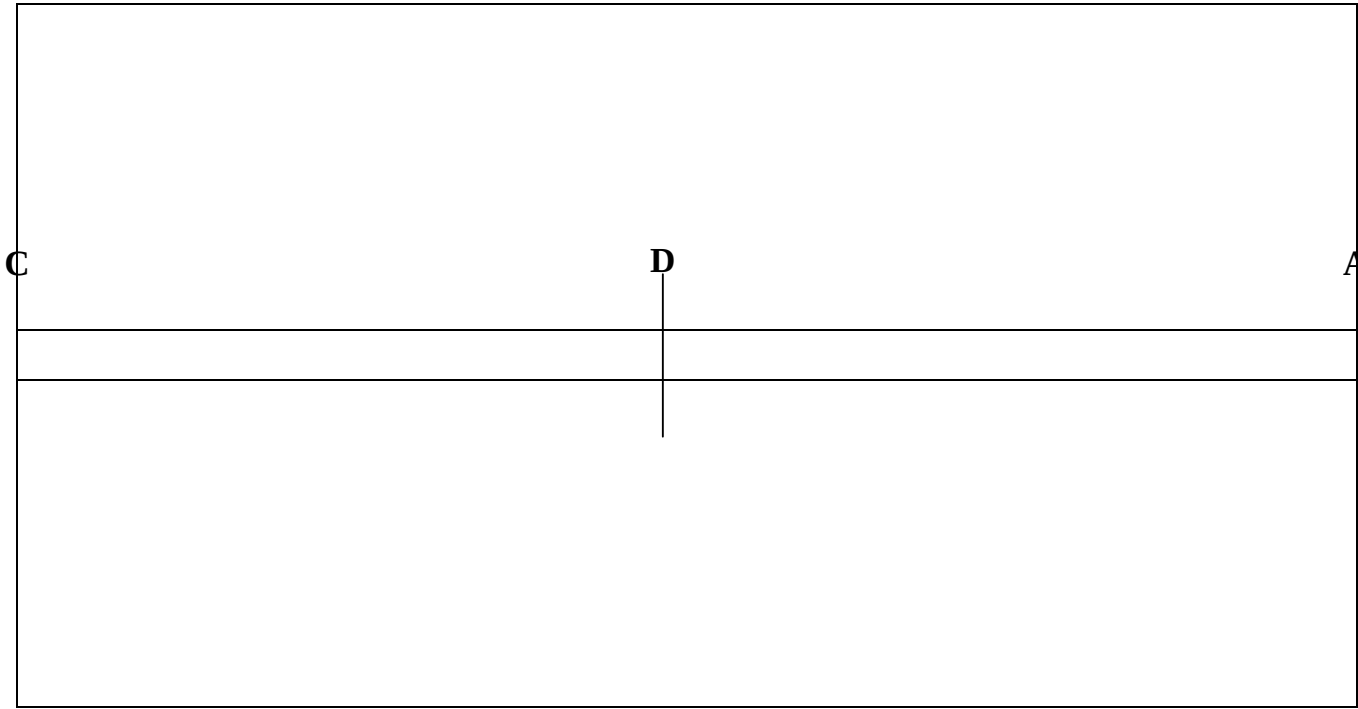
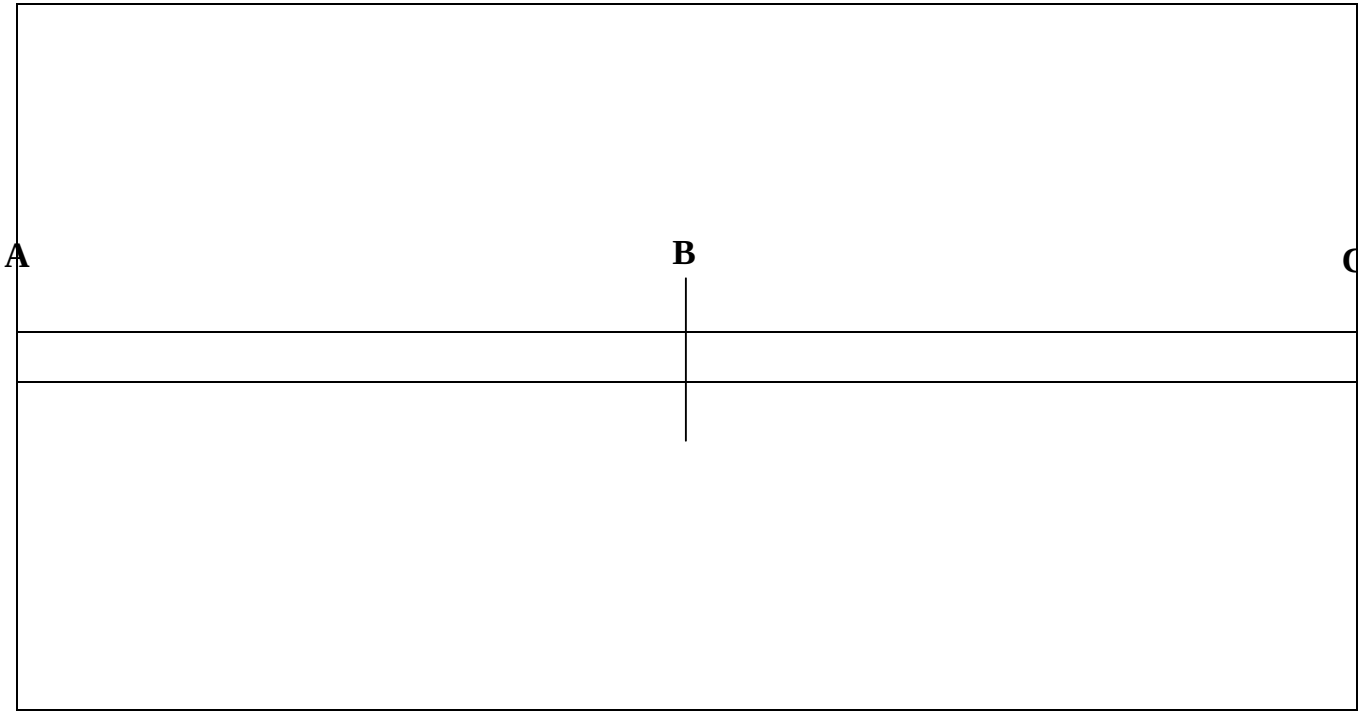
WELD FACE

A			B			C

C			D			A

P.T.O. [FOR ROOT]

PIPE ROOT FACE



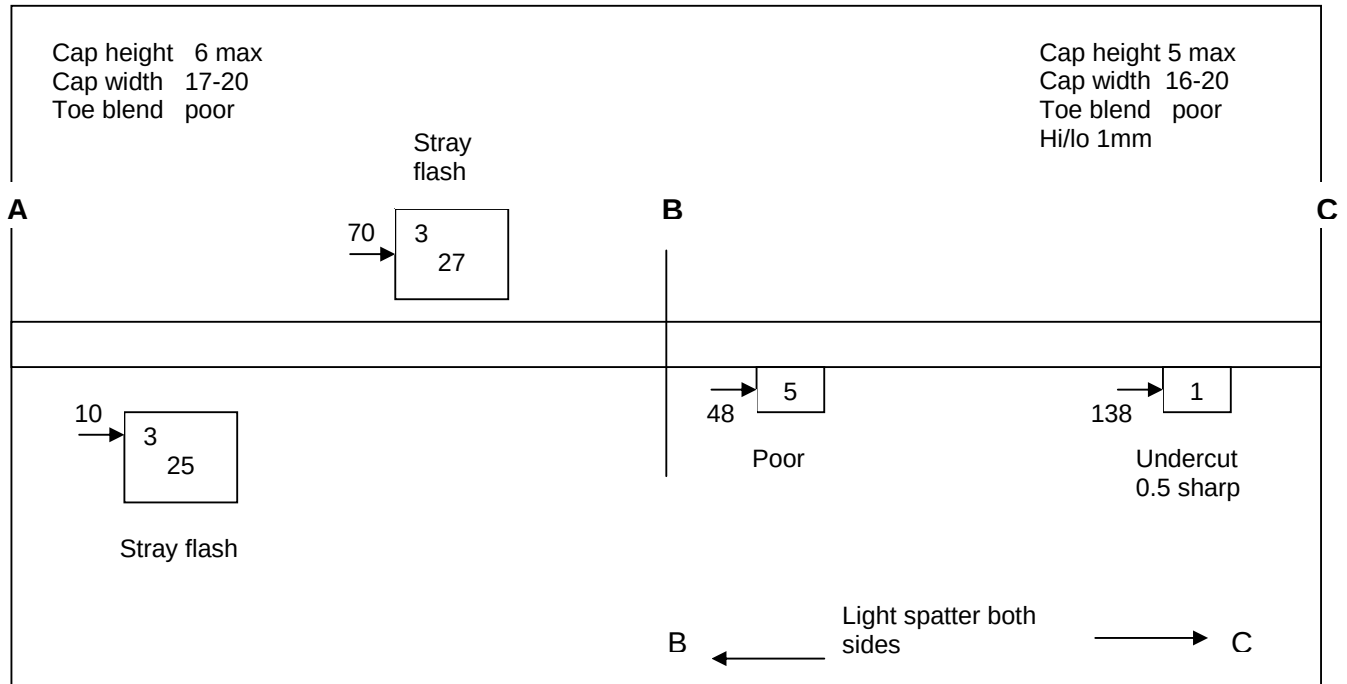
Visual Inspection Pipe Report

Name [Block capitals] STEVE HUGHES Signature SE Hughes Pipe Ident E9

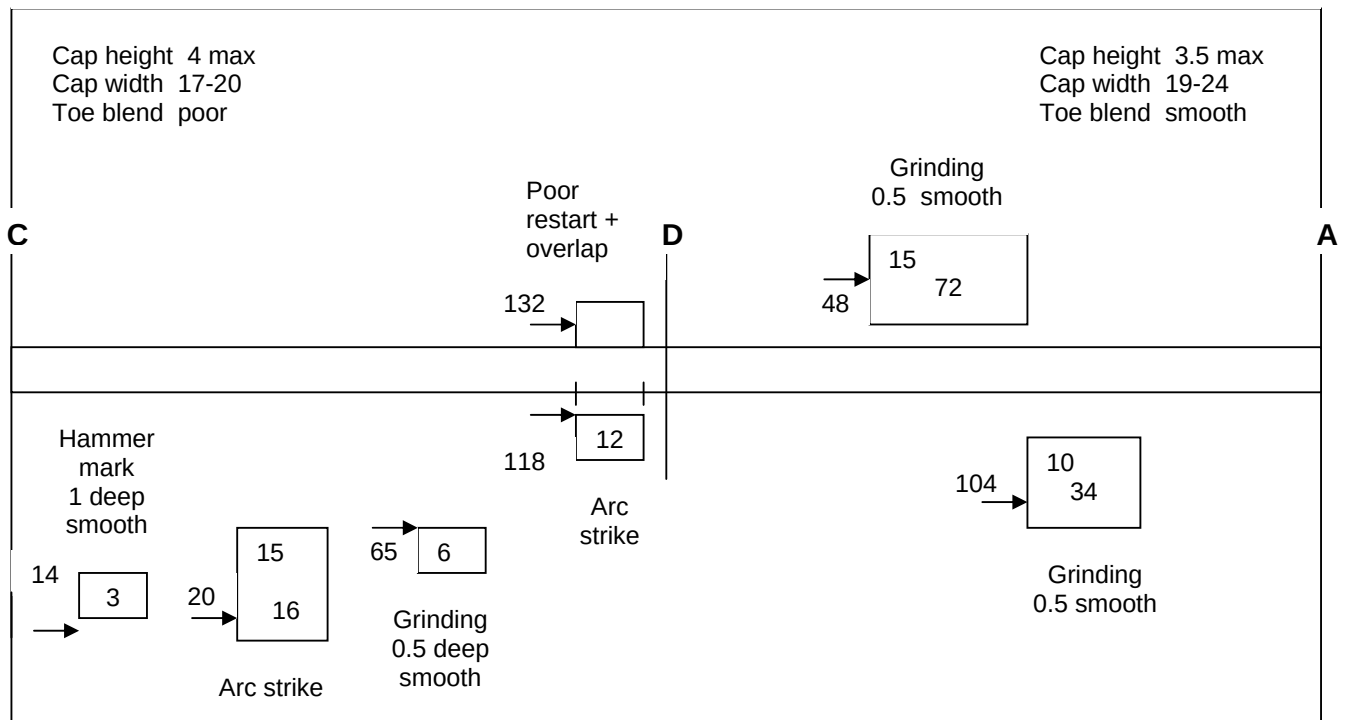
Code/Specification used YOUR CODE Welding Process MMA Joint type Single V

Welding position 5G Outside Ø and Thickness mm Date 12 March 03

Weld face

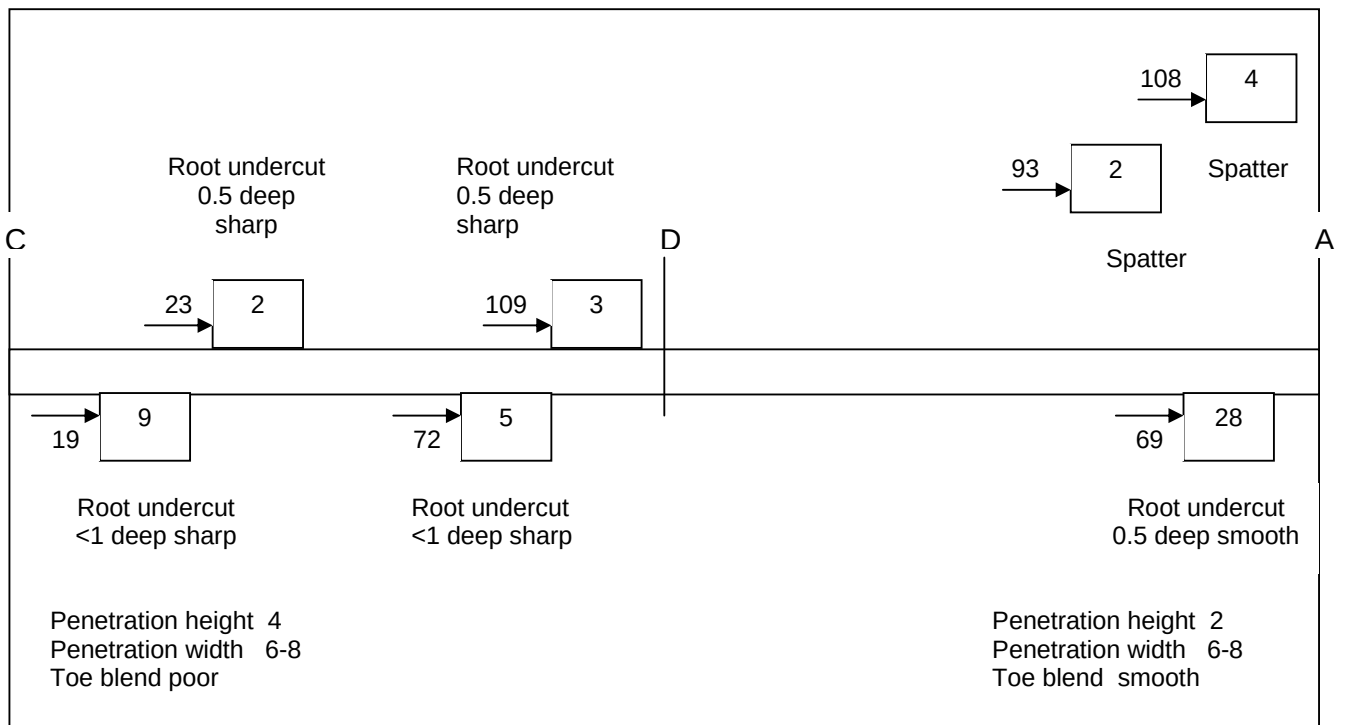
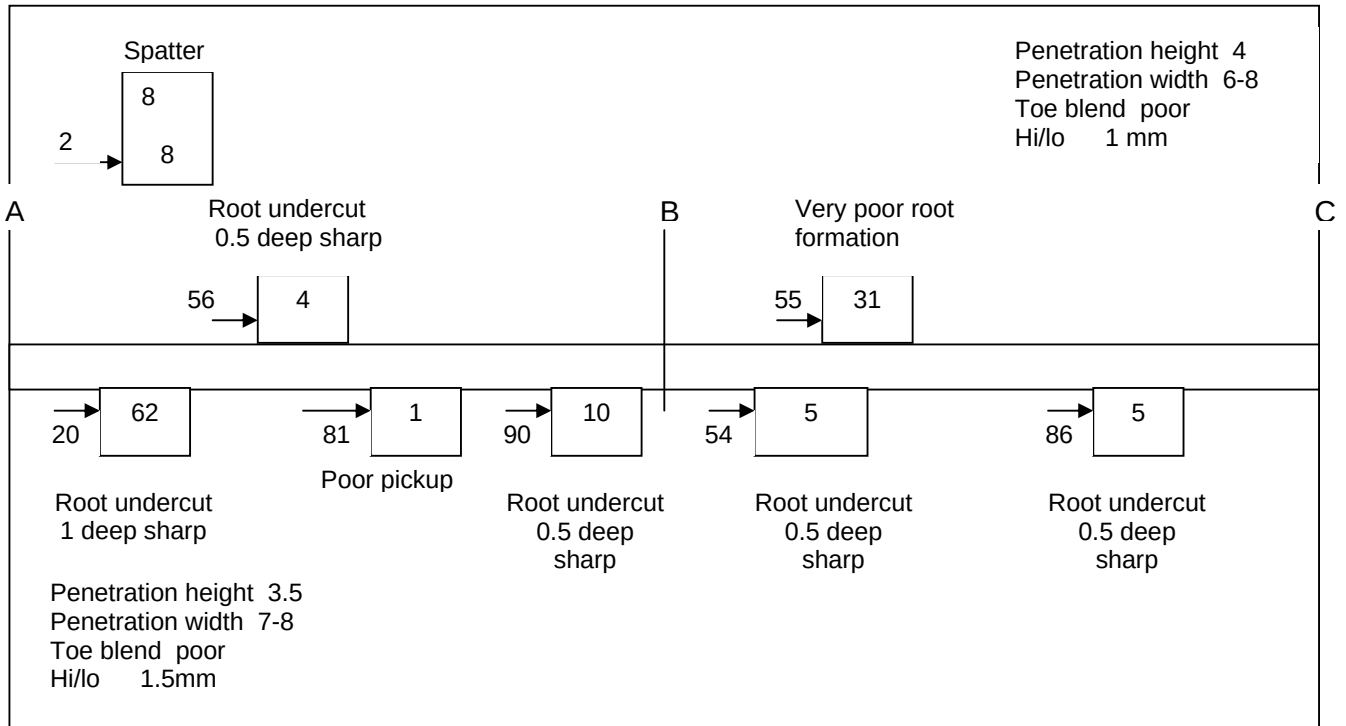


Smooth mechanical markings and pitting < 0.5mm deep is evident throughout parent materials over whole pipe



pto [for root]

Pipe root face



VISUAL INSPECTION PLATE REPORT

Name [Block capitals] _____ Signature _____ Test piece identification _____

Code/Specification used _____ Welding process _____ Joint type _____

Welding position _____ Length & thickness of plate _____ Date _____

M
E
A
S
U
R
E

F
R
O
M

T
H
I
S

D
A
T
U
M

E
D
G
E

WELD FACE

A

B

C

VISUAL PLATE REPORT

WELD ROOT

A

B

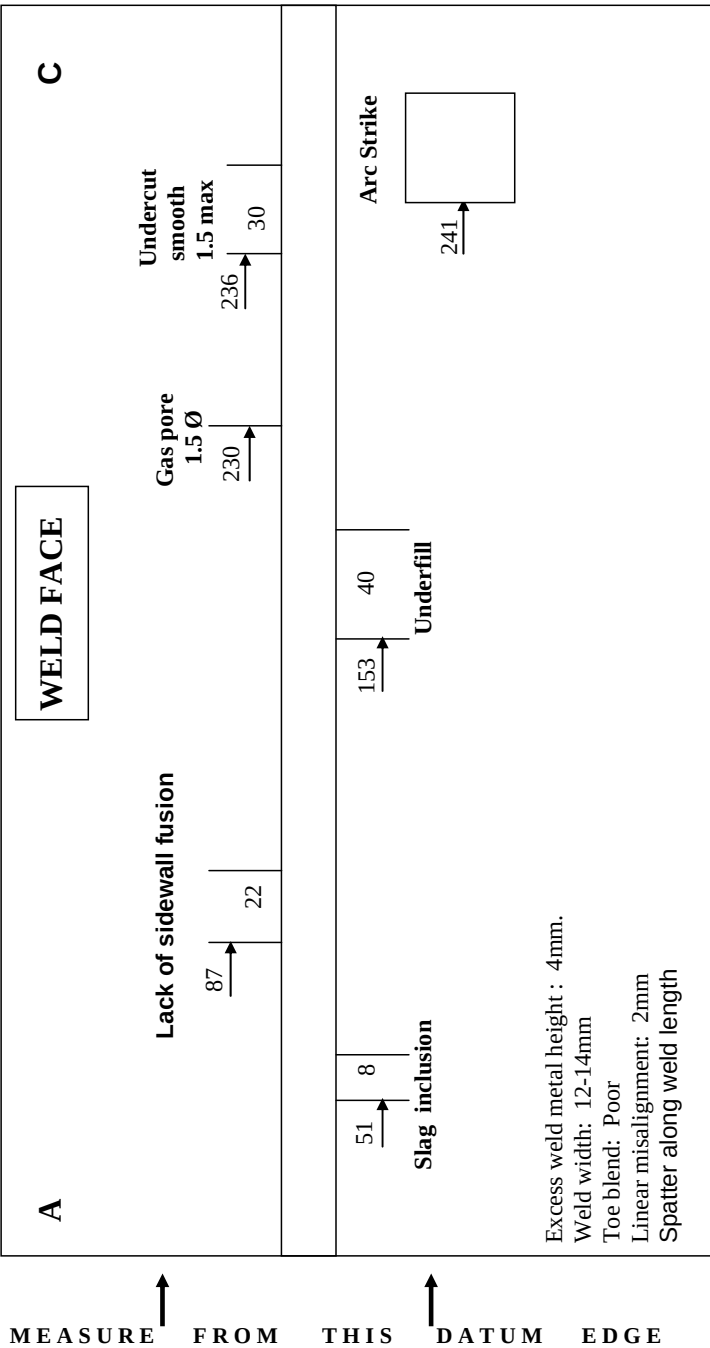
C

MEASURE FROM THIS DATUM ONLY



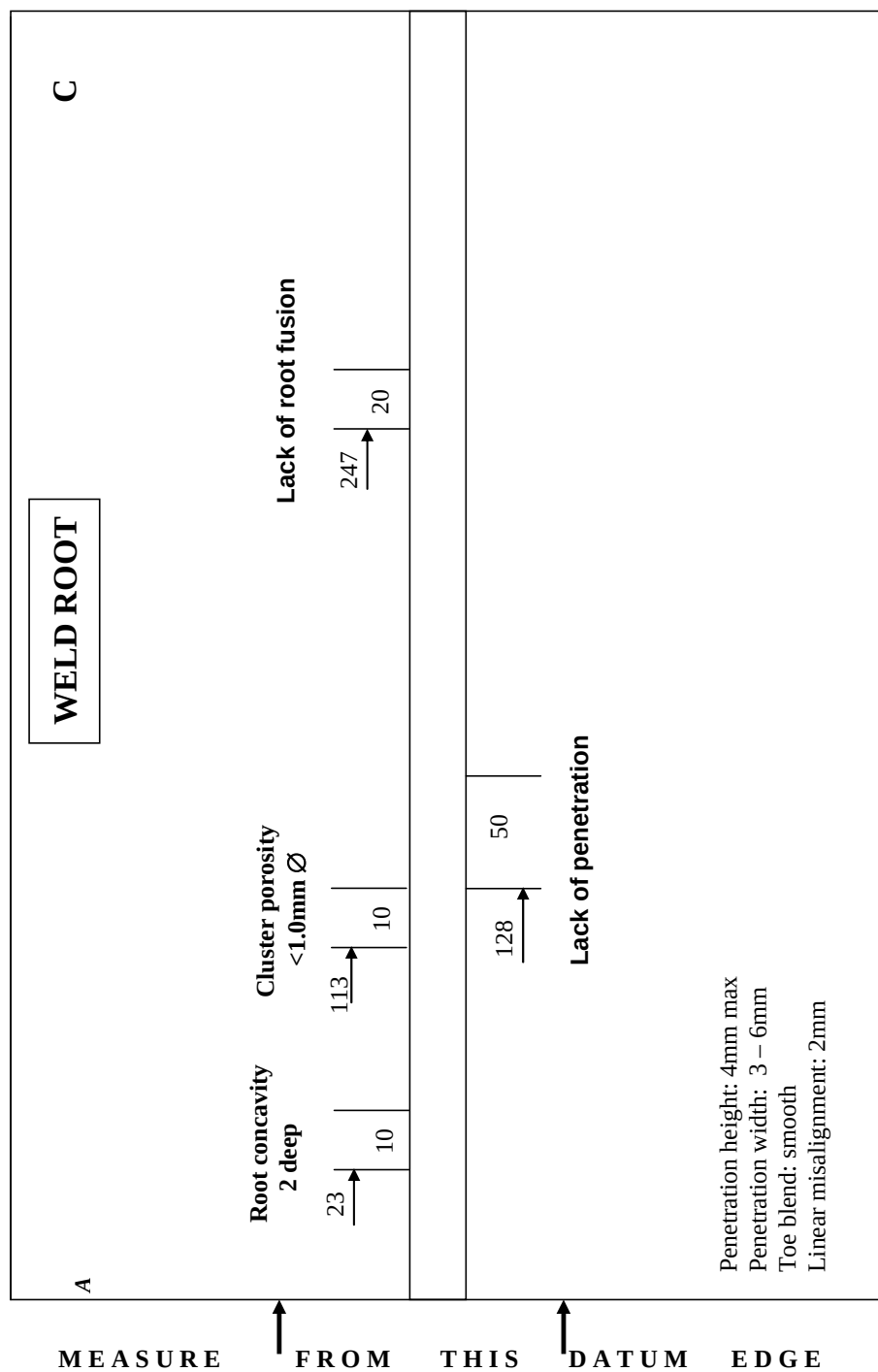
EXAMPLE PLATE REPORT

Name: [Block capitals] STUART DENT Signature: S DENT Test piece ident: 001
Code/Specification used: TWI 09-09-02 Welding process: MMA/SMAW Joint type: Single V Butt
Welding position: Flat/PA Length & thickness of plate: 300mm x 10 mm Date 8 Nov 2001



EXAMPLE PLATE REPORT

Page 2 of 3



Training Acceptance Levels for Plate, Pipe and Macro
D = depth L = length H = height t = thickness

Table number	Defect type	Acceptance levels plate and pipe		Acceptance levels macro only
		Remarks	Maximum allowance	Remarks
1	Excess weld metal	At no point shall the excess weld metal fall below the outside surface of the parent material. All weld runs shall blend smoothly.	Excess weld metal will not exceed H = 3mm in any area on the parent material, showing smooth transition at weld toes.	As for plate and pipe
2	Slag/silica inclusions	Slag inclusions are defined as non-metallic inclusions trapped in the weld metal or between the weld metal and the parent material.	The length of the slag inclusion shall not exceed 20mm continuous or intermittent. Accumulative totals shall not exceed 50mm	Slag not permitted
3	Undercut	Undercut is defined as a groove melted into the parent metal, at the toes of the weld excess metal, root or adjacent weld metal.	No sharp indications Smooth blend required. The length of any undercut shall not exceed 20mm continuous or intermittent. Accumulative totals shall not exceed 50mm. Max D = 2mm for the cap weld metal. Root undercut not permitted.	No sharp indications Smooth blend required
4	Porosity or Gas Cavities	Trapped gas, in weld metal, elongated, individual pores, cluster porosity, piping or wormhole porosity.	Individual pores ≥ 1 max. Cluster porosity maximum 20 ² mm total area. Elongated, piping or wormholes 15mm max. L continuous or intermittent.	Cluster porosity not permitted. Individual pores acceptable, max 3 indications
5	Cracks or Laminations	Transverse, longitudinal, star or crater cracks.	Not permitted	Not permitted
6	Lack of fusion	Incomplete fusion between the weld metal and base material, incomplete fusion between weld metal. (lack of inter-run fusion)	Surface breaking lack of side wall fusion, lack of inter-run fusion continuous or intermittent not to exceed 35mm. Accumulative totals not to exceed 35mm over a 300mm length of weld.	Not permitted
7	Arc strikes	Damage to the parent material or weld metal, from an unintentional touch down of the electrode or arcing from poor connections in the welding circuit.	ONLY 1 permitted	Not permitted
8	Mechanical damage	Damage to the parent material or weld metal, internal or external resulting from any activities.	Parent material must be smoothly blended Max. D = 2mm Only 1 location allowed No stray tack welds permitted	Not permitted
9	Misalignment	Mismatch between the welded or unwelded joint.	Max H = 2mm	As for plate and pipe
10	Penetration	Excess weld metal, above the base material in the root of the joint.	Max H $\leq$ 2mm	As for plate and pipe
11	Lack of root penetration	The absence of weld metal in the root area.	Not permitted	Not permitted
12	Lack of root fusion	Inadequate cross penetration of both root faces.	Lack of root fusion, not to exceed 30mm total continuous or accumulative.	Not permitted
13	Burn through	Excessive penetration, collapse of the weld root	Not permitted	Not permitted
14	Angular distortion	Distortion due to weld contraction	3mm max. Plate only	Accept
15	Root Shrinkage or Root concavity	Irregularities in the root profile due to shrinkage and contraction of the weld metal.	35mm maximum length 2mm maximum depth	Accept